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A Technical and Market study for WiMAX

Master's Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.

May 25th, 2009

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Preface

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Abstract

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Abstract:

Worldwide Interoperability for Microwave Access (WiMAX) is a broadband wireless technology based on IEEE 802.16-2004 and IEEE 802.16e-2005. This thesis is a study of WiMAX technology and market. The background of WiMAX development is introduced and opportunities and challenges for WiMAX are analyzed in the beginning. Then the thesis focuses on an overview of WiMAX technology, which addresses the physical layer, MAC layer and WiMAX network architecture. The deployment status is investigated in the fourth chapter. Both product development situation and market status are discussed in this section. In the last chapter, the future development trend of WiMAX is addressed.

Keywords: WiMAX OFDM OFDMA 4G IEEE 802.16-2004 IEEE 802.16e-2005 IEEE 802.16m

Content

List of acronyms and concepts

3GPP	3rd Generation Partnership Project
AAS	Advanced Antenna Systems
ACI	Adjacent Channel Interference
AES	Advanced Encryption Standard
AF	Application Function
AK	Authentication Key
AMC	Adaptive Modulation and Coding
AR	Access Router
ARQ	Automatic Repeat Request
ASN	Access Service Network
ASN-GW	ASN Gateway
BE	Best Effort
BS	Base Station
BW	Bandwidth
CALEA	Communications Assistance Law Enforcement Act
CCI	Co-Channel Interference
CMAC	Cipher-based Message Authentication Code
CoA	Care of Address
CP	Cyclic Prefix
CQICH	Channel-Quality Indicator Channel
CS	Convergence Sub-layer
CSI	Channel State Information
CSN	Connectivity Service Network
DC	Direct Current
Device-PSK	Device Pre-Shared Key
DFT	Discrete Fourier Transform
DHCP	Dynamic Host Control Protocol
DL	Downlink
DoA	Direction of Arrival
DOCSIS	Data Over Cable Service Interface Specification
DP	Decision Point

DPF	Data Path Function
EAP	Extensible Authentication Protocol
EMD	Evaluation Methodology Document
EMSK	Extended Master Session Key
EP	Enforcement Point
ErtPS	Extended Real-time Packet Service
ETSI	European Telecommunications Standards Institute
FBSS	Fast Base Station Switching
FCH	Frame Control Header
FDD	Frequency Division Duplexing
FTP	File Transfer Protocol
FTT	Fast Fourier Transform
FUSC	Full Usage of Sub-Carriers
HARQ	Hybrid-ARQ
HHO	Hard Handover
HIPERMAN	High-Performance Metropolitan Area Network
H-NSP	Home Network Service Provider
HO	Handoff Function
HoA	Home of Address
HUMAN	High-speed Unlicensed Metropolitan Area Network
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
ISI	Inter-Symbol Interference
LPF	Local Policy Function
LTE	Long Term Evolution
MAC	Media Access Control
MAN	Metropolitan Area Network
MAP	Media Access Protocol
MDHO	Macro Diversity Handover
MID	Mobile Internet Devices
MIMO	Multiple Input Multiple Output
MIP	Mobile IP
MPDU	MAC Protocol Data Unit

MS	Mobile Station
MSK	Shared Master Session Key
NLOS	Non–Line-of-Sight
nrtPS	Non–Real-Time Polling Service
NWG	Network Working Group
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple
PBH	Peak Busy Hour
PF	Policy Function
PHY	Physical Layer
PKM	Privacy and Key Management
PoA	Point of Attachment
PUSC	Partial Usage of Subcarriers
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RADIUS	Remote Access Dial-In User Service
RAT	Radio Access Technology
RP	Reference Points
RSA	Rivest-Shamer-Adleman
rtPS	real-time Polling Service
SAS	Smart Antenna System
SDD	System Description Document
SDU	Service Data Unit
SFA	Service Flow Authorization
SFM	Service Flow Management
SIMO	Single-Input-Multiple-Output
SLAAC	Stateless Address Auto-Configuration
SM	Spatial Multiplexing
SoC	System-on-Chip
SPWG	Service Provider Working Group
SRD	System Requirement Document
SS	Subscriber Station
STC	Space Time Coding
SUBC	Subscriber Root Key
TDD	Time Division Duplexing

TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TEK	Traffic Encryption Key
TGm	Task Group m
TUSC	Tile Usage of Subcarriers
UGS	Unsolicited Grant Services
UL	Uplink
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
VoIP	Voice Over Internet Protocol
WiMAX	Worldwide Interoperability for Microwave Access

1 Background of Broadband WiMAX

1.1 Evolution of Broadband wireless

We should understand the concept of broadband wireless and know the evolution of broadband wireless before we step into the WiMAX area. What is Broadband wireless? Broadband wireless is about offering broadband services by wireless solution. The term “Broadband wireless” stands for the combination of wireless technology and broadband access. There are two types of Broadband wireless. The first type is called fixed wireless broadband. Instead of using traditional fix-line transmission, it uses wireless transmission media to provide broadband services. The second type is called mobile broadband. It offers additional function with portability, nomadicity and mobility. During the evolution of broadband wireless, it has evolved through four stages that are narrowband wireless local-loop systems, first-generation line-of-sight (LOS) broadband systems, second-generation non-line-of-sight (NLOS) broadband systems and standards-based broadband wireless systems.

In the past two decades, the telecommunication industry have been developing fast both in technology area and business area. Wireless mobile services grew from 11 million subscribers worldwide in 1990 to more than 2 billion in 2005 [1]. At the same time, the Internet has spread all over the world. The requirement for high speed internet drives the broadband Internet access development. To replace the traditional wireline-access technology, telecommunication companies search for wireless solution for providing the broadband service. Many companies developed wireless access systems. Those systems varied in protocol, frequency spectrum, application supported, performance capabilities and some other parameters. But the broadband wireless has not been developing enormously because of lacking a common standard. WiMAX is developed to change the situation.

Worldwide Interoperability for Microwave Access (WiMAX) is a standard-based interoperable solution for wireless broadband. A WiMAX forum has been established to certify broadband wireless products for interoperability and compliance with a standard. WiMAX is based on wireless metropolitan area networking (WMAN) standards developed by the IEEE 802.16 group and adopted by both IEEE and the ETSI HIPERMAN group.

1.2 Background on IEEE 802.16 and WiMAX

The IEEE 802.16 group was established in 1998 to develop an air-interface standard for wireless broadband. The original 802.16 was finished in December 2001 which was based on a single-carrier physical (PHY) layer with a burst time division multiplexed (TDM) MAC layer. Many of the concepts related to the MAC were adapted for wireless from the cable modem DOCSIS (Data over Cable Service Interface Specification). After this, an amendment has been made to include NLOS (Non-Line-of-Sight) application in the 2GHz-11GHz band by using orthogonal frequency division multiplexing (OFDM) based physical layer. For the MAC layer, orthogonal frequency division multiple access (OFDMA) was added in this revision. In 2004, the IEEE802.16 group produced a new standard which is called IEEE 802.16-2004. It replaced all the previous versions and created the first WiMAX solution. Those WiMAX solutions based on IEEE 802.16-2004 targeted fixed applications and they were called as fixed WiMAX. In 2005, the group made an amendment to IEEE 802.16-2004 standard. This amendment added the mobility support in the standard. This revision is called IEEE 802.16e-2005. It offers the basis of the solution for nomadic and mobile application. Therefore, this revision is called as mobile WiMAX. Table 1.1 [2] shows the basic data for above-mentioned standards.

Table 1.1 Basic Data on IEEE 802.16 Standards

	802.16	**802.16-2004**	**802.16e-2005**
Status	Completed December 2001	Completed June 2004	Completed December 2005
Frequency band	10GHz–66GHz	2GHz–11GHz	2GHz–11GHz for fixed; 2GHz–6GHz for mobile applications
Application	Fixed LOS	Fixed NLOS	Fixed and mobile NLOS
MAC architecture	Point-to-multipoint, mesh	Point-to-multipoint, mesh	Point-to-multipoint, mesh
Transmission scheme	Single carrier only	Single carrier, 256 OFDM or 2,048 OFDM	Single carrier, 256 OFDM or scalable OFDM with 128, 512, 1,024, or 2,048 subcarriers
Modulation	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM
Gross data rate	32Mbps–134.4Mbps	1Mbps–75Mbps	1Mbps–75Mbps
Multiplexing	Burst TDM/TDMA	Burst TDM/TDMA/ OFDMA	Burst TDM/TDMA/ OFDMA
Duplexing	TDD and FDD	TDD and FDD	TDD and FDD
Channel band-widths	20MHz, 25MHz, 28MHz	1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz	1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz
Air-interface designation	Wireless MAN-SC	Wireless MAN-SCa Wireless MAN-OFDM Wireless MAN-OFDMA Wireless HUMANa	Wireless MAN-SCa Wireless MAN-OFDM Wireless MAN-OFDMA Wireless HUMANa
WiMAX implementation	None	256 - OFDM as Fixed WiMAX	Scalable OFDMA as Mobile WiMAX

a. Wireless HUMAN (wireless high-speed unlicensed MAN) is similar to OFDM-PHY (physical layer) but mandates dynamic frequency selection for license-exempt bands.

After standards were completed, the WiMAX forum designed the certification profiles for fixed WiMAX and mobile WiMAX. They are showed in the Table 1.2 [2]. Those profiles specified the frequency band, channel bandwidth and duplexing mode.

Table 1.2 Fixed and Mobile WiMAX Initial Certification Profiles

Band Index	**Frequency Band**	**Channel Bandwidth**	**OFDM FFT Size**	**Duplexing**	**Notes**
		Fixed WiMAX Profiles			
1	3.5 GHz	3.5MHz	256	FDD	Products already certified
		3.5MHz	256	TDD	
		7MHz	256	FDD	
		7MHz	256	TDD	
2	5.8GHz	10MHz	256	TDD	
		Mobile WiMAX Profiles			
1	2.3GHz–2.4GHz	5MHz	512	TDD	Both bandwidths must be supported by mobile station (MS)
		10MHz	1,024	TDD	
		8.75MHz	1,024	TDD	
2	2.305GHz– 2.320GHz, 2.345GHz– 2.360GHz	3.5MHz	512	TDD	
		5MHz	512	TDD	
		10MHz	1,024	TDD	
3	2.496GHz– 2.69GHz	5MHz	512	TDD	Both bandwidths must be sup-ported by mobile station (MS)
		10MHz	1,024	TDD	
4	3.3GHz–3.4GHz	5MHz	512	TDD	
		7MHz	1,024	TDD	
		10MHz	1,024	TDD	
5	3.4GHz–3.8GHz, 3.4GHz–3.6GHz, 3.6GHz–3.8GHz	5MHz	512	TDD	
		7MHz	1,024	TDD	
		10MHz	1,024	TDD	

2 Opportunity and challenge

In previous two sections, we have been through the background of WiMAX. In the deployment of WiMAX, we face both opportunities and challenges. In the following section, we will analyze WiMAX from commercial and technical challenges perspective.

2.1 Opportunity

The service providers have been searching for a more cost effective wireless solution for broadband access. During the past decade, many wireless access systems have been developed. They varied in performance capabilities, protocols, frequency spectrum and so on. Most of them have not been successful. But WiMAX is expected to become a common standard for broadband wireless technology.

WiMAX has business opportunity both in developed countries and underdeveloped countries. In developed countries and regions, such as USA, West European regions, relatively good infrastructure is available for basic voice communication service and internet access. People demand higher speed and more flexibility in accessing the variable services. WiMAX is such a solution which can meet the requirement in this market. WiMAX can be an even bigger success in the developing countries where nearly two-thirds of the people are living. In those countries or regions, the infrastructure is not good enough even for the basic voice communication service and there is a constant search for low cost solutions. This is a large and attractive market for every company and WiMAX provides a cost effective solution for this market.

WiMAX Forum released the WiMAX Technology Forecast for 2007 to 2012 as showed in Table 2.1. It is expected that the growth will be strong in all regions. At the same time, the numbers of operators and countries that start using WiMAX are also increasing as showed in Figure 2.1 [3].

Table 2.1 WiMAX Users by Region (millions) 2007-2012 Users= subscribers adjusted to reflect multiple users per subscription						
Region	2007	2008	2009	2010	2011	2012
North America	2.61	4.03	6.25	9.59	14.79	22.62
Americas	0.66	1.18	2.14	3.92	7.17	12.97
Asia Pacific	1.39	.284	5.99	12.96	28.17	60.45
Europe	1.35	2.34	4.07	7.08	12.23	21.01
Africa/Middle East	0.30	0.65	1.46	3.32	7.50	16.60
TOTAL	6.32	11.04	19.91	36.88	69.87	133.66

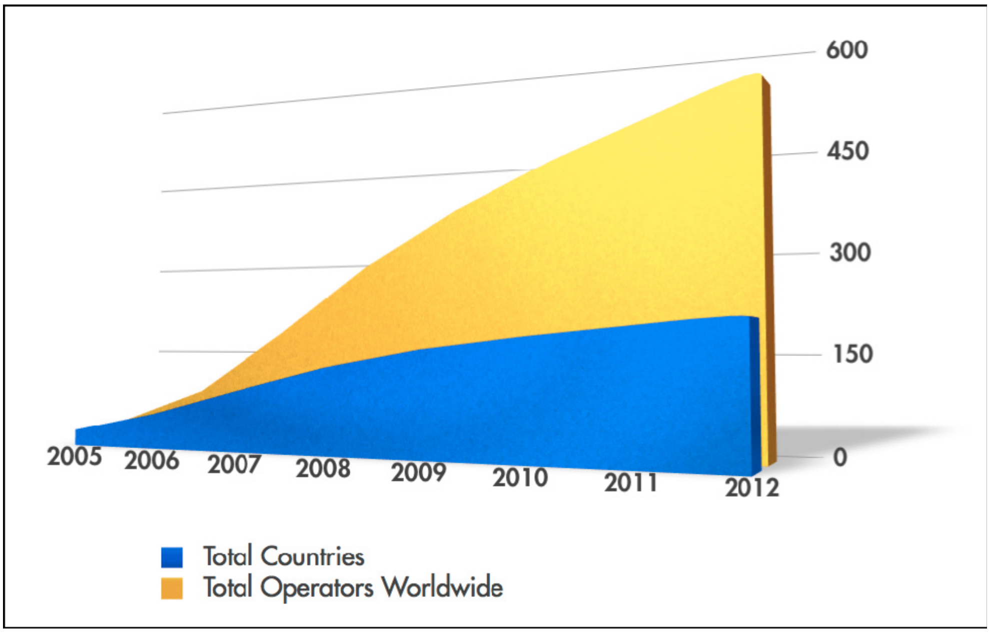


Figure 2.1 Expected WiMAX operators and countries 2007-2012

2.2 Challenge

Though there are great opportunities for WiMAX, the challenges exist at the same time. The challenges are both on business area and technology area.

2.2.1 Business challenge

The Fixed WiMAX faces the rising challenges from traditional wired broadband solutions, such as DSL and cable modem, especially in the mature markets like United States where good fixed line infrastructure is already deployed in most of the areas. DSL and cable modem technology are also developing fast to offer higher data rate and better service quality. The increasing data rates supported by these wired broadband solutions allow providers to offer not only data, voice applications but also entertainment TV and so on. WiMAX has advantage in terms of low cost infrastructure, but wired broadband solutions also benefit from the declining cost on customer premise equipment (CPE) in long term.

For mobile WiMAX, the biggest challenge comes from 3G technologies which are being deployed widely by mobile operators. The mobile operators are more likely to use 3G which is a relatively mature technology instead of using WiMAX. To compete with 3G, some innovative applications and new attractive business models need to be developed for WiMAX, for more comparative analysis, see [4][5]. Besides the competition from 3G, mobile WiMAX has the challenges on device development. It is very important to have a wide variety of terminal devices to achieve the success. Intel started shipping WiMAX chipset in 2004 but it will take some time to convince the device producers to build WiMAX chipset into their devices. To be competitive against 3G, WiMAX should look for new possible devices which have been not deployed with wireless broadband features such as MP3 players, video players and so on.

There are also challenges in getting the common compatible spectrum band. There are different allocation and regulations for broadband spectrum worldwide. Although 2.5G Hz, 3.5G Hz and 5.8G Hz bands are allocated in many regions of world, new allocations are needed in many other countries.

2.2.2 Technical challenge

WiMAX also have variety of challenges in the technical area. They are listed in the followings.

- **Wireless radio channel:** The first and most fundamental challenges come from the wireless radio channel. In wired communication channels, the signals are guided by the cable which is relatively stable and robust. Wireless radio channel is an unpredictable channel which is affected by many other factors such as obstructions, terrain undulations, relative motion between the transmitter and the receiver, interference from other signals, noise, and so on. Those factors cause many problems which need to be solved, for example, pathloss, shadowing, multipath fading, intersymbol interference, Doppler spread, Additive white Gaussian noise (AWGN) and so on.
- **Spectrum scarcity:** As discussed in the last section, there is only limited amount of spectrum that is allocated for WiMAX. The need for accommodating increasing number of users and offering high rate applications challenges the designers to use the spectrum more efficiently.
- **Quality of service:** WiMAX needs to support a variety of applications such as voice, data, video and multimedia. Each of the applications has different requirements in terms of data rate, traffic flow, packet loss, delay and so on. Therefore, it is a challenge to balance the allocation of resource on different applications and users. Besides the QoS requirement across the wireless link, QoS has to be delivered end-to-end across the network which includes switching a variety of aggregation, switching, and routing elements between the communication end points.
- **Mobility:** The challenge for mobility is mainly due to handling roaming and handoff process. It is essential to find the right balance between the resource consumption and the performance. IP based network becomes

more important in the future. Therefore, IP-based mobility management will be another challenge.

- **Power consumption:** To be portable, mobility is a prerequisite. Besides mobility, the power efficiency is another key issue. The requirement of low power consumption challenges designers to search for power efficient transmission schemes, power-saving protocols, computationally less intensive signal-processing algorithms, low-power circuit-design and fabrication, and battery technologies with long life.
- **Security:** Security is essential for any communication system. From the subscribers' perspective, the privacy and data integrity are the primary security requirement. From service providers' perspective, they want to prevent unauthorized use of the network.
- **Support IP in wireless:** IP-based networking protocol becomes more and more popular in modern communication systems because of their advantages in cost and flexibility for supporting various applications. However, challenges are faced in making IP-based networking more bandwidth efficient, more reliable on QoS and more flexible in handling the changes in the network.

Though the information theory, communication hardware and signal processing algorithms have been developing fast, the designers are still facing challenges to meet the user's increasing expectation. To achieve successes and be more competitive than the other wireless broadband solutions, WiMAX should handle all those challenges properly.

3 Technical overview of WiMAX

3.1 The main feature of WiMAX

WiMAX has a lot of good features in terms of deployment options and potential service offerings. Some of the main features are as follows.

- **OFDM-based physical layer:** The WiMAX physical layer is based on OFDM (orthogonal frequency division multiplexing). It reduces the multipath interference and makes WiMAX possible to operate in NLOS (non-line-of-sight) conditions.
- **Very high peak data rates:** WiMAX can offer very high peak data rates. When using 20MHz wide spectrum, the PHY data rate can reach 70Mbps. When 10MHz wide spectrum is used and operated in TDD with 3:1 downlink-to-uplink ratio, the 25Mbps for downlink and 6.7Mbps for uplink peak data rate can be achieved. These peak PHY data rates can be achieved by using 64 QAM modulations with rate 5/6 error-correction coding.
- **Scalable bandwidth and data rate support:** WiMAX can be scaled to various available bandwidths. The scalability of WiMAX also offers the possibility to support user roaming across different networks that may have different bandwidth allocations.
- **Adaptive modulation and coding (AMC):** WiMAX can adapt between different modulation and coding scheme based on channel conditions. The adaptation algorithm typically calls for the use of the highest modulation and coding scheme that can be supported by the signal-to-noise and interference ratio at the receiver such that each user is provided with the highest possible data rate that can be supported in their respective links [2].

- **Link-layer retransmissions:** WiMAX supports automatic retransmission requests (ARQ) at the link layer. All transmitted packets need to be acknowledged by the receiver. Those unacknowledged packets are assumed to be lost and need to be retransmitted. This feature increases the reliability of the connections.

- **Support for TDD and FDD:** WiMAX also supports both time division duplexing (TDD) and frequency division duplexing. We note that currently there is FDD profiling only for fixed WiMAX.

- **Orthogonal frequency division multiple accesses (OFDMA):** OFDMA is used as the multiple access technique by Mobile WiMAX. In OFDMA, frequency diversity and multi-user diversity are used to improve the system capacity.

- **Flexible and dynamic per user resource allocation:** WiMAX dynamically allocate the resources based on the demands from users.

- **Support for advanced antenna techniques:** WiMAX support the use of multiple-antenna techniques, such as beamforming, space-time coding and spatial multiplexing. By deploying multiple antennas at the transmitter and the receiver, the system capacity and spectral efficiency can be improved.

- **Quality-of-service support:** WiMAX support different services, such as constant bit rate, variable bit rate, real-time, non-real-time traffic flows and so on.

- **Robust security:** WiMAX supports strong encryption, using Advanced Encryption Standard (AES) and has a robust privacy and key-management protocol. The system also offers very flexible authentication architecture based on Extensible Authentication Protocol (EAP). It allows for a variety of user credentials, such as username/password, digital certificates, and so on.

- **Support for mobility:** The Mobile WiMAX support mobility by improving performance of power control, uplink subchannelization and frequent channel estimation
- **IP-based architecture:** The WiMAX defined the network following the IP-based architecture.

3.2 WiMAX Physical Layer (PHY)

3.2.1 OFDM Basics

WiMAX is based on orthogonal frequency division multiplexing (OFDM). OFDM is a multiplexing technique which divides the bandwidth into multiple frequency subcarriers. The basic idea of OFDM can be showed as Figure 3.1. In OFDM, a high-bit-rate data stream is divided into N parallel lower bit rate streams. Then those streams are modulated and transmitted in separate subcarriers. The symbol duration on each subcarrier increases to $T=NT_s$. If N is large enough to ensure that the symbol duration time exceeds the channel delay spread, T>>τ, then it reduces the Inter Symbol Interference (ISI).

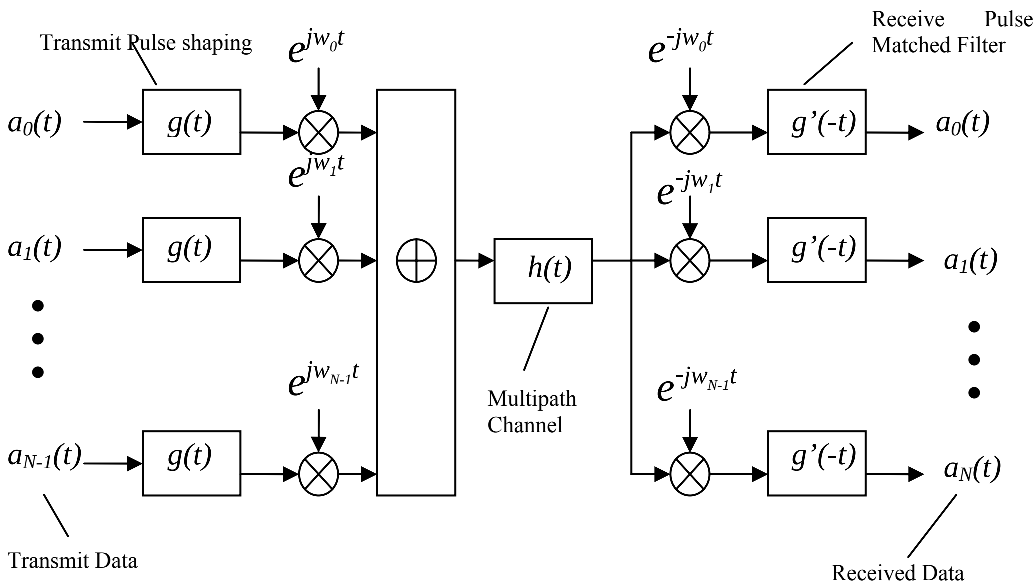


Figure 3.1 Basic Architecture of an OFDM System

Instead of adding the overlapping subcarrier channels, OFDM uses orthogonal subcarriers over the symbol duration to eliminate the intercarrier interference. When the number of subcarriers N is large enough to allow the subcarrier bandwidth to be much less than the coherence bandwidth B_c, that is, $B/N<<B_c$, subcarriers experience relatively flat fading.

However, in order to completely eliminate ISI, cyclic prefix (CP) is used as a guard interval between OFDM symbols. As long as CP duration is longer than the multipath delay spread, ISI-free channel can be achieved. The CP is a copy of the last symbols and put it in the beginning of the data symbol as shown in Figure 3.2. But CP is overhead and it causes power wastage and a decrease in bandwidth efficiency. The amount of power wasted depends on how large a fraction the guard time occupies in OFDM symbol duration. Therefore, larger symbol duration and more subcarrier save power and improve bandwidth efficiency.

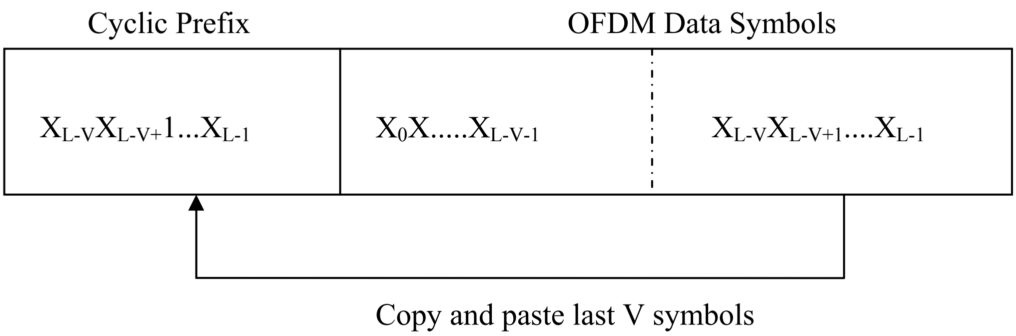


Figure 3.2 Insert Cyclic Prefix

Too many resources are used if the subcarriers are transmitted separately on N independent radio frequency bands. To solve this problem, OFDM uses an efficient computational technique, discrete Fourier transforms (DFT), and its efficient implementation which is commonly known as the fast Fourier transforms (FFT). The FFT and inverse FFT (IFFT) are used to create a multitude of orthogonal subcarriers using a single radio frequency.

Fixed WiMAX and mobile WiMAX are based on different physical layer. Fix WiMAX based on IEEE 802.16-2004 uses a 256 FFT-based OFDM physical layer.

Mobile WiMAX based on IEEE 802.16e-2005 uses a scalable OFDMA-based physical layer. In mobile WiMAX, the FFT sizes vary from 128 to 2048. OFDMA will be discussed in the next section. Parameters for OFDM-PHY and OFDMA-PHY are showed in the Table 3.1, for details, see [6].

Table 3.1 OFDM Parameters Used in WiMAX

Parameter	**Fixed WiMAX OFDM-PHY**	**Mobile WiMAX Scalable OFDMA-PHY**[a]			
FFT size	256	128	512	1,024	2,048
Number of used data subcarriers[b]	192	72	360	720	1,440
Number of pilot subcarriers	8	12	60	120	240
Number of null/guardband subcarriers	56	44	92	184	368
Cyclic prefix or guard time (Tg/Tb)	1/32, 1/16, 1/8, 1/4				
Oversampling rate (Fs/BW)	Depends on bandwidth: 7/6 for 256 OFDM, 8/7 for multiples of 1.75MHz, and 28/25 for multiples of 1.25MHz, 1.5MHz, 2MHz, or 2.75MHz.				
Channel bandwidth (MHz)	3.5	1.25	5	10	20
Subcarrier frequency spacing (kHz)	15.625	10.94			
Useful symbol time (μs)	64	91.4			
Guard time assuming 12.5% (μs)	8	11.4			
OFDM symbol duration (μs)	72	102.9			
Number of OFDM symbols in 5 ms frame	69	48.0			

a. Boldfaced values correspond to those of the initial mobile WiMAX system profiles.
b. The mobile WiMAX subcarrier distribution listed is for downlink PUSC (partial usage of subcarrier).

3.2.2 Symbol structure and subchannelization

The OFDM symbol structure has three types of subcarriers as shown in Figure 3.3.

1. **Data subcarriers** are used for data transmission
2. **Pilot subcarriers** are used for carrying the pilot symbols. The pilot symbols can be used for channel estimation and channel tracking.
3. **Null subcarriers** have no power allocated to them. This type includes guard subcarriers at the edge of the spectrum and DC subcarriers. The guard subcarriers are used to reduce the interference between adjacent channels. The DC subcarriers are used to prevent saturation effects or excess power consumption at the amplifier.

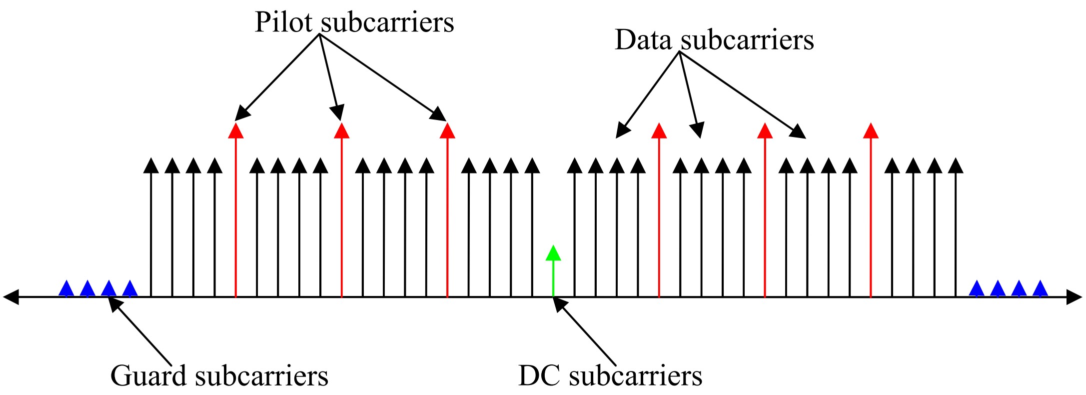


Figure 3.3 OFDM symbol structure

Fixed WiMAX is based on OFDM-PHY and it only allows a limited form of subchannelization in the uplink. However, mobile WiMAX is based on OFDMA-PHY and it allows subchannelization in both the uplink and the downlink. The minimum frequency resource unit allocated by the base station is subchannel, also called a slot that is equal to 48 data tones (subcarriers). Different subchannels can be allocated to different users according to multiple-access mechanism in Mobile WiMAX.

Subchannels can be either formed by subcarriers which are adjacent to each other or by subcarriers which are distributed pseudo-randomly throughout the frequency band. Those two types of permutations are called as contiguous permutation and diversity permutation. Better frequency diversity is achieved by using diversity permutation. Diversity permutation is more useful for mobile applications. Contiguous permutation is better for beamforming and gaining multiuser diversity. It is more suitable for fixed or low mobility applications.

Diversity permutations include Downlink Full Usage of Subcarriers (DL FUSC), Downlink Partial Usage of Subcarriers (DL PUSC), Uplink Partial Usage of Subcarriers (UL PUSC) and Tile Usage of Subcarriers (TUSC). In DL FUSC, 48 data carriers are used to create different subchannels. They are distributed evenly throughout the frequency band as showed in Figure 3.4 [2]. In DL PUSC, all subcarriers are divided into six groups first. Permutation of subcarriers to create subchannels is performed independently within each group. By this approach, groups are logically separated from each other. DL PUSC is showed in Figure 3.5 [2]. In UL PUSC, all subcarriers are divided into tiles. Each tile has four subcarriers over three OFDM symbols. The subcarriers in each tile are divided into 8 data subcarriers and 4 pilot subcarriers. Then the tiles are renumbered randomly and divided into six groups. Figure 3.6 [2] shows the UL PUSC. TUSC is a downlink subcarrier permutation mode which is same as the uplink PUSC. If closed loop advanced antenna systems (AAS) are to be used with the PUSC mode, explicit feedback of the channel state information (CSI) from the MS to the BS would be required even in the case of TDD, since the UL and DL allocations are not symmetric, and channel reciprocity cannot be used [2]. TUSC makes the downlink permutation is symmetric to the UL PUSC. In this case, the explicit CSI feedback is not need.

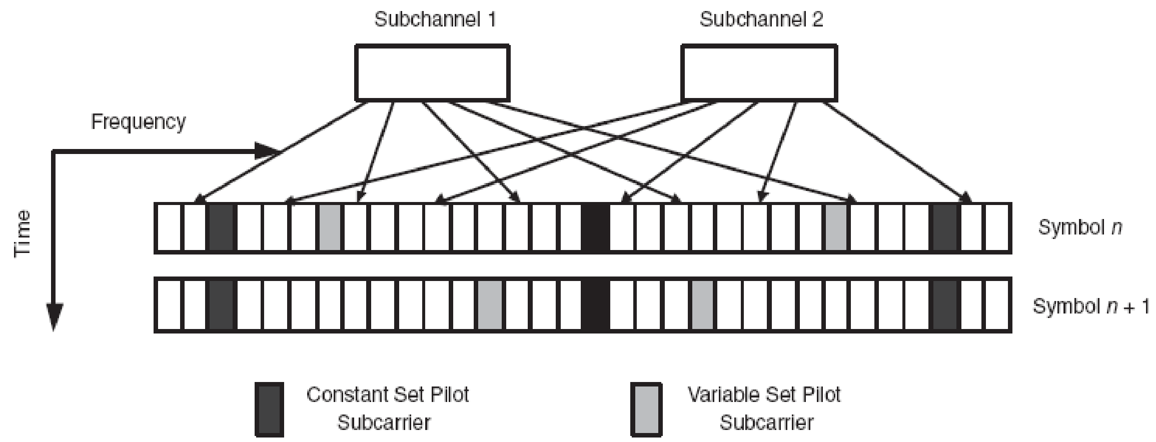


Figure 3.4 DL FUSC subcarrier permutation

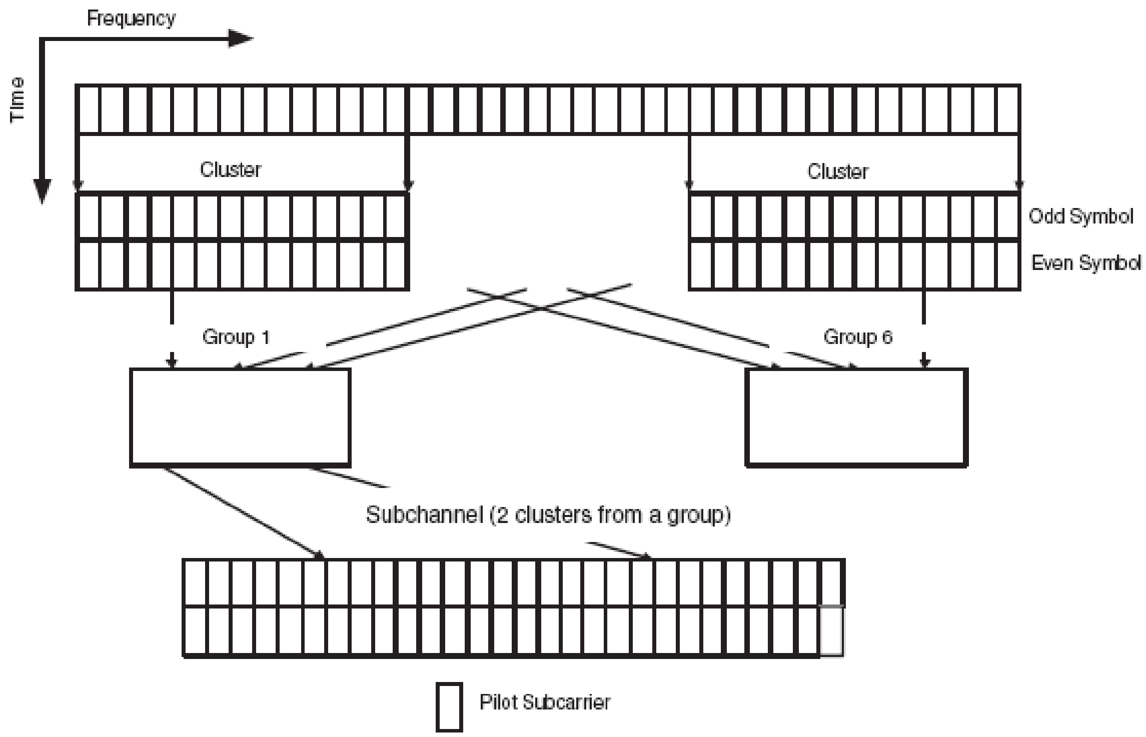


Figure 3.5 DL PUSC subcarrier permutation

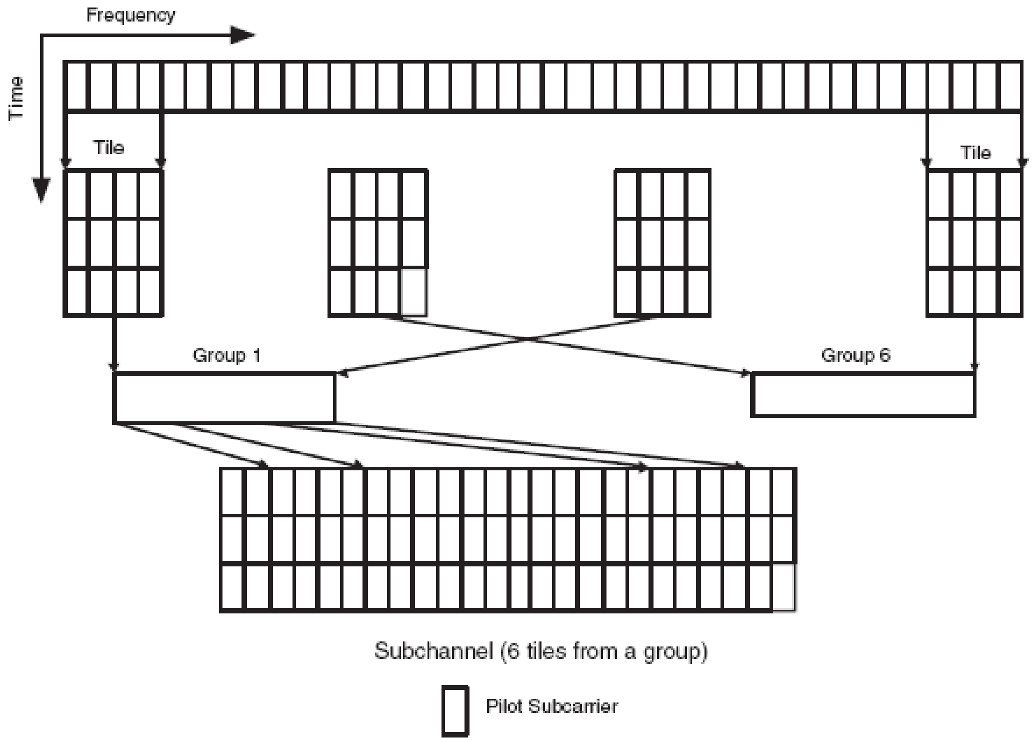


Figure 3.6 UL PUSC subcarrier permutations

The contiguous permutations include DL AMC (downlink adaptive modulation and coding) and UL AMC (uplink adaptive modulation and coding). DL AMC and UL AMC have the same structure. In AMC permutation, one bin has 9 adjacent subcarriers. Eight of them are data subcarriers and one is pilot subcarrier. Adjacent bins constitute a band. An AMC subchannel consists of six bins from the same band. Thus the subchannel can have 6 bins over one symbol, 3 bins over 2 symbols, 2 bins over 3 symbols or 1 bin over 6 symbols. This permutation improves the overall system capacity by enabling the multi-user diversity.

In general, diversity subcarrier permutations perform well in mobile applications while contiguous subcarrier permutations are better for low mobility environments.

3.2.3 Frame Structure

WiMAX supports both TDD and FDD operation. However, TDD is preferred in most of the deployments. FDD is only used in some current fixed WiMAX. TDD enables the adjustment between downlink and uplink while FDD always has fixed downlink and uplink bandwidths. TDD has channel reciprocity for better support of link adaptation, MIMO and other closed loop advanced antenna technologies. TDD only requires a single channel for both downlink and uplink while FDD needs a pair of channels. Transceiver designs for TDD are simpler and less expensive. The downside of TDD is the need for synchronization across multiple base stations to reduce interference.

The Figure 3.7 shows the OFDM frame structure for TDD. The downlink subframe and uplink subframe are separated by guard symbol to prevent DL and UL transmission collisions. The downlink subframe starts with preamble which is used for synchronization and initial channel estimation. The frame control header (FCH) follows the preamble. It contains the frame configuration information, such as MAP message length, the modulation, coding scheme and the usable subcarriers. The downlink MAP and uplink MAP provide subchannel allocation and other control information. Since these data are critical, it is necessary to send them by more reliable link. However, it could form a significant overhead, when a large number of users with small packets need to be specified. To deal with overhead impact, mobile WiMAX system can optionally use multiple sub-MAPs which are dedicated on sending the control message over high rates link.

The uplink subframe consists of several burst from different users. The ranging subchannel is used for mobile station (MS) to perform closed loop time, frequency, and power adjustment as well as bandwidth. The fast feedback channel which is also called channel quality indicator channel (CQICH) is used for the subscriber station (SS) to feed back channel quality information. The acknowledged channel is allocated for the MS to feed back downlink hybrid automatic repeat request (HARQ) acknowledgement.

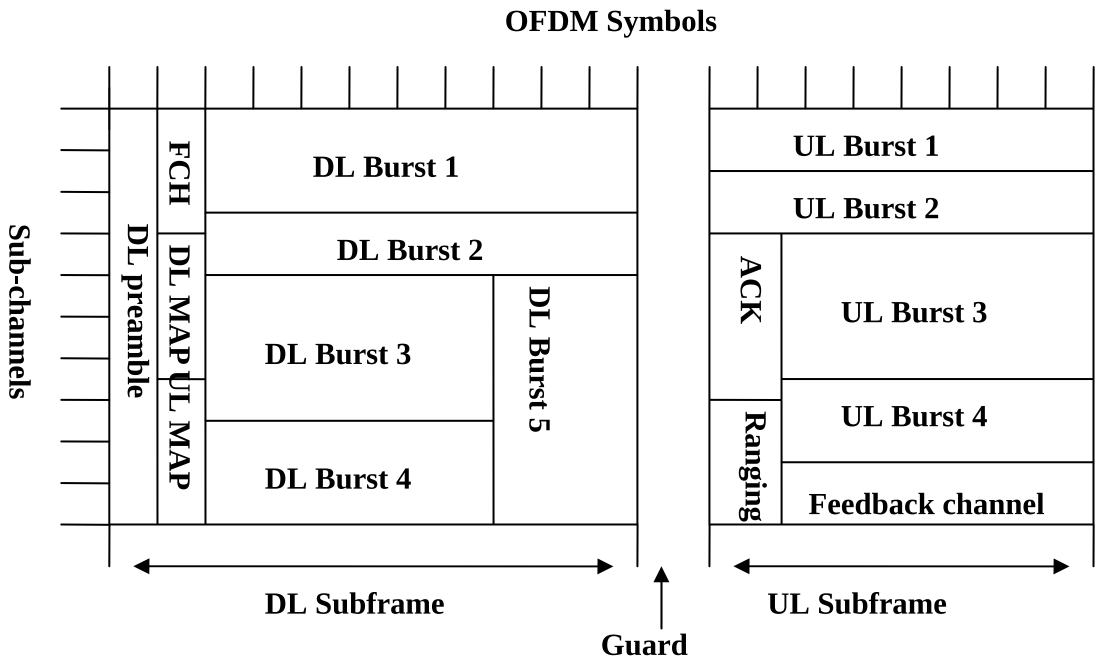


Figure 3.7 TDD frame structure

3.3 WiMAX MAC-Layer

MAC layer is the second layer in the open systems interconnection model. It is the interface between the higher transport layers and the physical layer. The PHY layer is to deliver information bits from the transmitter to the receiver by using physical medium. MAC layer is responsible for controlling the links created for different applications while the different kinds of applications are not considered by PHY layer. MAC layer receives service data units (SDU) from the upper layer and organize them into MAC protocol data units (MPDU) for transmission over the air. It does the reverse for the received data from PHY. In the following sections, the main functions of the MAC layer for WiMAX will be introduced.

3.3.1 Quality of Service

WiMAX MAC layer provides the QoS support. The concept is based on the QoS design for Data over Cable Service Interface Specification (DOCSIS) standard.

Connection oriented MAC architecture is used to build the QoS control function. All downlink and uplink connections are controlled by the serving BS. Before the transmission starts, a unidirectional link is created between the MAC layer of BS and MS. The connection is identified by a connection identifier which is a temporary address for data transmission over the link. A service flow is defined by WiMAX as a unidirectional flow of packets with a particular set of QoS parameters. It is identified by service flow identifier (SFID). The QoS can be evaluated in different parameters as traffic priority, maximum sustained traffic rate, maximum burst rate, minimum tolerable rate, scheduling type, QRQ type, maximum delay, tolerated jitter, service data unit type and size, bandwidth request mechanism to be used and so on. For more details, see [7].

Five different categories are defined by WiMAX as followings to support variable applications.

- **Unsolicited grant services (UGS):** This is designed to support real time service flows which generate fixed-size data packets on a periodic basis, such as T1/E1 and VoIP.
- **Real time polling service (rtPS):** This is designed to support real-time services, such as streaming audio or video which generate variable data packets on a periodic basis.
- **Non real time polling service (nrtPS):** This is designed to support those services which can tolerant delay, such as File Transfer Protocol FTP.
- **Best effort (BE) service:** This is designed to support those services which do not have strict QoS requirements, such as Web browsing service. Data is sent whenever resources are available.
- **Extended real-time polling rate service (ErtPS):** This is designed to support real time applications which have variable data rates and require guaranteed data rates and delay, such as VoIP with silence suppression.

The following table shows the QoS parameters defined for each service type and the application examples.

Table 3.2 Service Flows Supported in WiMAX		
Service Flow Designation	**Defining QoS Parameters**	**Application Examples**
Unsolicited grant services (UGS)	Maximum sustained rate Maximum latency tolerance Jitter tolerance	Voice over IP (VoIP) without silence suppression
Real-time Polling service (rtPS)	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Traffic priority	Streaming audio and video, MPEG (Motion Picture Experts Group) encoded
Non-real-time Polling service (nrtPS)	Minimum reserved rate Maximum sustained rate Traffic priority	File Transfer Protocol (FTP)
Best-effort service (BE)	Maximum sustained rate Traffic priority	Web browsing, data transfer
Extended real-time Polling service (ErtPS)	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Jitter tolerance Traffic priority	VoIP with silence suppression

3.3.2 Mobility management

There are three handoff methods supported in IEEE 802.16e-2005. They are hard handover (HHO), fast base station switching (FBSS) and macro diversity handover (MDHO). HHO is mandatory while FBSS and MDHO are optional [7].

In HHO, the MS makes a radio frequency scan to measure the signal quality of neighboring base stations. This scan is done in the scanning intervals which are allocated by MS. At the same time, the MS can perform a ranging to initiate the connection with other neighboring base stations. Whenever a handover decision is made based on the measurement, the MS synchronizes with the downlink transmission of the targeted neighboring BS and perform a ranging if it was not done in the scan, then it terminates the connection with the previous BS.

In FBSS, the MS maintains a list of BSs which is called active set. The MS continuously monitors the active set, does the ranging and keeps the connections ID with each of them. Among the BSs in the active set, the MS only communicates with one BS which is defined as anchor BS. When a handover is needed, the connection is switched from one BS to another BS without explicitly performing handoff signaling. The MS reports the selected anchor BS through CQI channel.

MDHO is similar with FBSS. However, the MS communicates with all the BSs in the active set. In the downlink, multiple downlink data received by MS are combined. In the uplink, the MS sends data to all the BSs and selection diversity is performed to choose the best link.

Both FBSS and MDHO have better performance than HHO, but they require that the base stations in the active or diversity set be synchronized, use the same carrier frequency, and share network entry-related information.

3.3.3 Power management

Mobile WiMAX defines two features to save the power for portable devices. They are sleep mode an idle mode. In sleep mode, the MS turns itself off for certain period of time to save power. This time is decided by the MS and the BS. Besides the energy saving, sleep mode also save the BS radio resources. To perform handover while in sleep mode, the MS scan other BSs to collect information. Three power saving classes are defined in WiMAX as followings.

- In Class 1, the sleep window is exponentially increased from minimum to maximum. This is used when the MS is doing best-effort and non-real-time traffic.
- In Class 2, sleep window is of fixed length. This is used for UGS service.
- In Class 3, there is only a one-time sleep window. This is used for multicast traffic or management traffic where the timing of the traffic is known.

In idle mode, the MS can be completely turned off. It receives the downlink broadcast data periodically without even registration at any BS. When downlink traffic arrives, MS is paged by BS. The MS is assigned to a paging group by BS before going into idle mode and it wakes up to update the paging group periodically. Idle mode saves more power than sleep mode. Additionally, it eliminates handover traffic from inactive MSs.

3.3.4 Security

Security has been highlighted in WiMAX from the beginning. The best security technology has been used to guarantee the security communication in the system. The key aspects of the security features are as follow.

- **Device/user authentication:** To prevent the unauthorized use, a flexible authentication method is used by WiMAX. The authentication framework is based on the Internet Engineering Task Force (IETF) EAP. It supports many credentials, such as smart cards, digital certificate and user name/ password. The mobile devices have built-in X.509 digital certificates that contain their public key and MAC address. The operators use this to identify the devices and then use username/ password or smart card for the authentication.
- **Key management protocol:** The Privacy and Key Management Protocol Version 2 (PKMPV2) is used to secure the data exchange between BS and MS. PKM uses X.509 digital certificates and RSA (Rivest-Shamer-Adleman) public-key encryption algorithms to securely perform key exchanges between the BS and the MS [2].
- **Control message protection:** Control messages are protected by suing message digest schemes, such as AES-based CMAC (cipher-based message authentication code) or MD5 (message digest 5 algorithm)-based HMAC (hash-based message authentication codes).

- **Support for fast handover:** A pre-authentication is performed between the MS and its targeted BS to reduce the handover time. A three-way handshake scheme is used to optimize the reauthentication mechanisms for supporting fast handover. It prevents the man-in-the middle attacks.

3.4 WiMAX network architecture

We have been discussing PHY and MAC layers in the last two sections. However, to build an interoperable broadband wireless network, interoperable network architecture is needed to deal with the end-to-end service issues such as IP connectivity, session management, QoS, security and mobility management. Network Working Group (NWG) in WiMAX forum was established to develop such network architecture. A three-stage standards development process has been used by WiMAX Forum. In stage 1, service requirements are specified for the network. These requirements are developed within the WiMAX Service Provider Working Group (SPWG). The architecture that meets the service requirements is developed in stage 2. Stage 3 gives all the details of protocol used in the architecture. The fourth version of the release 1 has been just released. At the same, the release 1.5 is under development. In this section, we will focus on the network architecture which is showed in stage 2 [8]. More details for stage 1 and stage 3 can be found in [9] [10].

3.4.1 Network Reference Model

Tenets have been set for developing the WiMAX network architecture. They are defined from different aspects, such as service and application, security, mobility and handover, QoS, manageability, performance and so on. The development of WiMAX network architecture should follow the tenets and the results should meet the requirement from all aspects. More detailed exposition for the tenets can be found in [8].

Based on the tenets, network reference model (NRM) was developed. NRM is a logical representation of the network architecture. It identifies the functional entities and reference points over which interoperability is achieved between functional entities. The intent of the NRM is to achieve the interoperability and allow multiple implementation options for a given functional entity. NRM consists of three major parts which are MS/SS, access service network and connectivity service network as showed in Figure 3.8 [8]. Mobile Station or Subscriber Station is the Mobile or stationary equipment which is used to connect the subscriber equipment and a base station. It could be a host or multiple hosts.

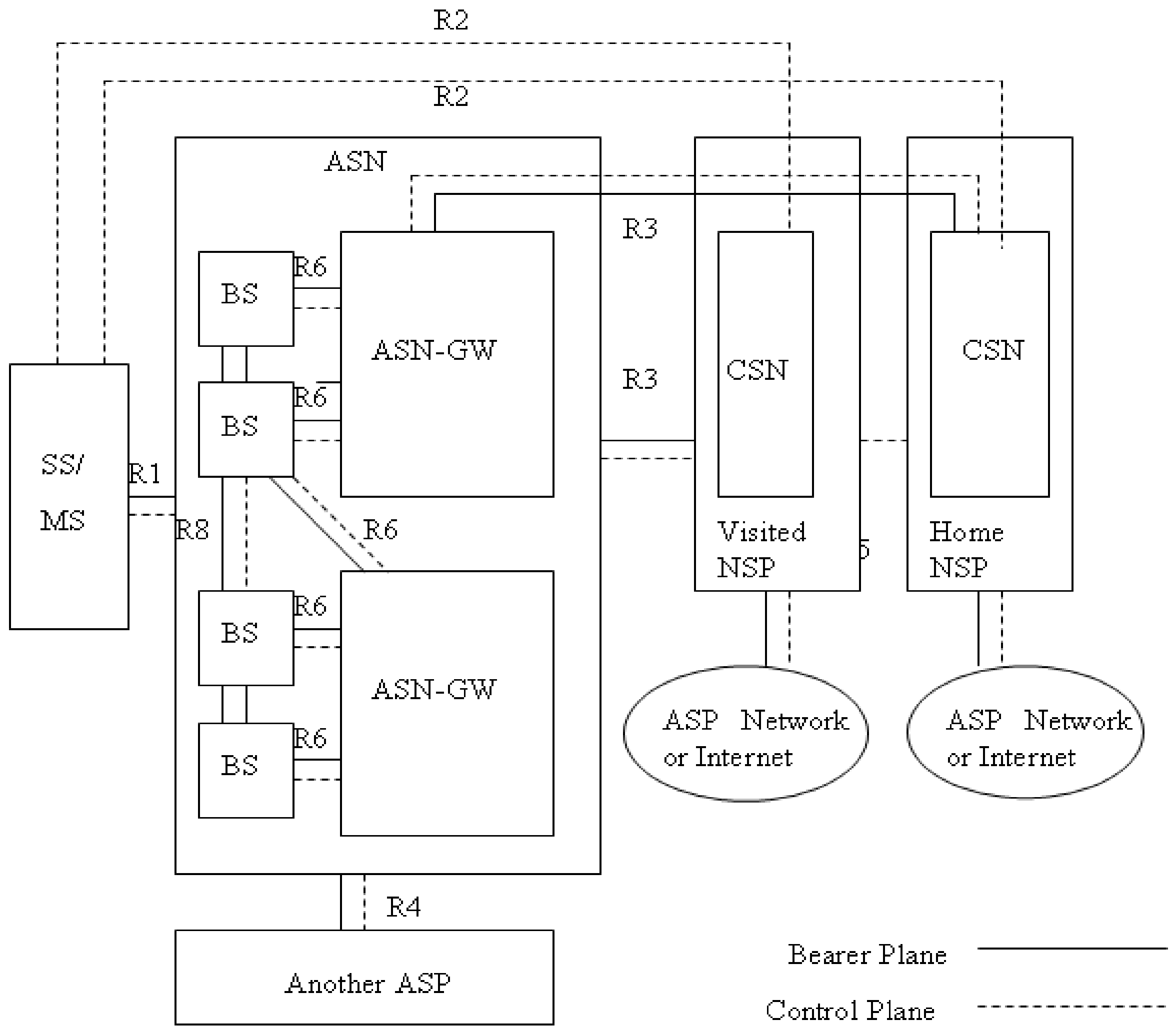


Figure 3.8 Network reference model

3.4.1.1 Access Service Network (ASN) functions

ASN is a complete set of network functions needed to provide radio access to a WiMAX subscriber. ASN is owned by a network access provider (NAP). It performs the following functions as defined in [8].

- WiMAX Layer 2 connectivity with WiMAX MS
- Transfer of AAA messages to WiMAX subscriber's Home Network Service Provider (H-NSP) for authentication, authorization and session
- Network discovery and selection of the WiMAX subscriber's preferred NSP
- Relay functionality for establishing Layer 3 connectivity with a WiMAX MS (i.e. IP address allocation)
- Radio Resource Management
- For a portable and mobile environment, ASN also needs to support ASN anchored mobility, Connectivity Service Network (CSN) anchored mobility, paging and ASN-CSN tunneling

Figure 3.8 also shows the decomposition for ASN. The ASN consists of one or more BS and one or more ASN Gateway (ASN-GW). BS is a logical entity that embodies a full instance of the WiMAX MAC and PHY in compliance with the IEEE 802.16 suite of applicable standards and may host one or more access functions. The ASN-GW is defined as a logical entity that represents an aggregation of Control Plane functional entities that are either paired with a corresponding function in the ASN, a resident function in the CSN or a function in another ASN. The ASN-GW can be optionally decomposed into two groups of functions which are decision point (DP) functions and enforcement point (EP) as showed in Figure 3.9. EP includes bearer plane functions and the DP includes non-bearer plane functions.

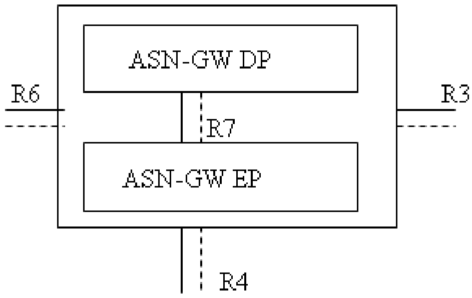


Figure 3.9 ASN-GW decomposition diagram

NRM defines three different profiles for ASN. The profile maps the ASN functions into BS and ASN-GW. Table 3.3 shows the comparison between three profiles. More details on ASN profiles can be found in [8].

Table 3.3 Functional Decomposition of the ASN in Various Release 1 Profiles

Functional Category	Function	ASN Entity Name		
		Profile A	**Profile B**	**Profile C**
Security	Authenticator	ASN-GW	ASN	ASN-GW
	Authentication relay	BS	ASN	BS
	Key distributor	ASN-GW	ASN	ASN-GW
	Key receiver	BS	ASN	BS
IntraASN Mobility	Data Path function	ASN-GW & BS	ASN	ASN-GW and BS
	Handover function	ASN-GW & BS	ASN	BS
	Context server & Client	ASN-GW & BS	ASN	ASN-GW and BS
L3 Mobility	MIP Authentication Relay	ASN-GW	ASN	ASN-GW
	MIP foreign agent	ASN-GW	ASN	ASN-GW
Radio resource management	Radio resource controller	ASN-GW	ASN	BS
	Radio resource agent	BS	ASN	BS
Paging	Paging agent	BS	ASN	BS
	Paging controller	ASN-GW	ASN	ASN-GW
QoS	Service flow authorization	ASN-GW	ASN	ASN-GW
	Service flow manager	BS	ASN	BS

3.4.1.2 Connectivity Service Network (CSN) functions

CSN is owned by Network Service Provider. It is defined as a set of network functions that provide IP connectivity services to the WiMAX subscribers. CSN may contain network elements such as routers, AAA proxy/servers, user databases and interworking gateway MSs. Its functions include:

- MS IP address and endpoint parameter allocation for user sessions
- Internet access
- AAA proxy or server
- Policy and Admission Control based on user subscription profiles
- ASN-CSN tunneling support
- WiMAX subscriber billing and inter-operator settlement
- Inter-CSN tunneling for roaming
- Inter-ASN mobility
- WiMAX services such as location based services, connectivity for peer-to-peer services, provisioning, authorization and/or connectivity to IP multimedia services and facilities to support lawful intercept services such as those compliant with Communications Assistance Law Enforcement Act (CALEA) procedures.

3.4.1.3 Reference points

A reference point (RP) is a conceptual link that connects two groups of functions that reside in different functional entities of an ASN, CSN or MS [8]. A RP only becomes a physical interface when the functional entities on either side of it are contained in different physical MSs. In Figure 3.8, 8 RPs have been showed.

- R1 consist of the protocols and procedures between MS and ASN as per the air interface specifications. R1 may include additional protocols related to the management plane.
- R2 consist of protocols and procedures between the MS and CSN associated with Authentication, Services Authorization and IP Host Configuration management.
- R3 consists of the set of Control Plane protocols between the ASN and the CSN to support AAA, policy enforcement and mobility management capabilities. It also encompasses the Bearer Plane methods to transfer user data between the ASN and the CSN.
- R4 consists of the set of Control and Bearer Plane protocols originating/terminating in various functional entities of an ASN that coordinate MS mobility between ASNs and ASN-GWs. R4 is the only interoperable RP between similar or heterogeneous ASNs.
- R5 consists of the set of Control Plane and Bearer Plane protocols for internetworking between the CSN operated by the home NSP and that operated by a visited NSP.
- R6 consists of the set of control and Bearer Plane protocols for communication between the BS and the ASN-GW. The Bearer Plane consists of intra-ASN data path between the BS and ASN gateway. The Control Plane includes protocols for data path establishment, modification, and release control in accordance with the MS mobility events. However, when protocols and primitives over R8 are defined, MAC states will not be exchanged over R6.
- R7 consists of the optional set of Control Plane protocols e.g., for AAA and Policy coordination in the ASN gateway as well as other protocols for co-ordination between the two groups of functions identified in R6.

The decomposition of the ASN functions using the R7 protocols is optional.

- R8 consists of the set of Control Plane message flows and optionally Bearer Plane data flows between the base stations to ensure fast and seamless handover. The Bearer Plane consists of protocols that allow the data transfer between Base Stations involved in handover of a certain MS. The Control Plane consists of the inter-BS communication protocol in line with IEEE 802.16e-2005, March 2006 [11] and 802.16g [12] (802.16g is under development in the IEEE.) and additional set of protocols that allow controlling the data transfer between the Base Stations involved in handover of a certain MS. Messages and protocols shall be informatively specified for applicable ASN profiles in WiMAX Forum Network Architecture.

3.4.2 IP addressing

IP addressing refers to the way to deliver the Point of Attachment (PoA) address to the MS. Dynamic Host Control Protocol (DHCP) is used as main IP addressing mechanism for WiMAX network. Alternatively, the home CSN may allocate IP addresses to an ASN via AAA and then it is delivered to MS by DHCP. For fixed access, static IP address may assigned by manual provisioning in the MS or via DHCP. Dynamic IP address assignment is based on DHCP. The DHCP should reside in CSN domain that allocates the PoA address. For nomadic access, Dynamic IP address assignment is used. It is based on DHCP. The DHCP server should reside in home or visited CSN domains. The DHCP proxy may reside in ASN and retrieves IP host configuration information during access authorization. For mobile access, it allows PoA IP address assignment based on DHCP for Proxy-MIP based SS/MSs. The DHCP server resides in CSN domain. In this case, the PoA address and IP host configuration information should be derived using DHCP.

The DHCP can also reside in ASN and retrieves IP host configuration information and home address during Access Authentication AAA exchange with home NSP.

IPv6 in a WiMAX network can be operated in different ways. The packet convergence sublayer (CS) specified in the IEEE802.16d/e specification is used for transport of all packet based protocols. The ASN includes an IPv6 access router (AR) functionality and MS get a routable IP address from AR. When using mobile IPv6, the MS obtains the care of address (CoA) from the ASN and a home address (HoA) from the home CSN. Then the MS use either the CoA or HoA as its PoA address. Fixed access allows two types of PoA IP address allocations via static/manual configuration, DHCPv6 and stateless address auto-configuration (SLAAC). Nomadic access allows stateful address auto-configuration and stateless address auto-configuration. Mobile access uses stateful address auto-configuration and SLAAC. More details on IPv6 address management in [8].

3.4.3 Security

WiMAX network architecture should be designed in such a way that end-to-end security of the service should be guaranteed. AAA framework is based on IETF specification which defines the protocols and procedures for authentication, authorization and accounting. AAA framework provides the authentication service, authorization service and accounting service to the WiMAX network.

In RFC2904 [13], three models for AAA deployment have been described. They are agent model, pull model and push model. The main difference between the models is how the suppliant and authentication server communicate and how the control information are configured into the bearer plan MSs. Among these three models, pull model is recommended for AAA deployments in WiMAX networks. Figure 3.10 shows the pull model in non-roaming case. In this model, it contains four steps. MS sends a request to NAS function in ASN, and the request is forwarded to AAA server in CSN. AAA server evaluates the request and gives an answer back to NAS. Then NAS provisions the bearer plane and tells MS that it is ready. In roaming cases, one or more AAA proxy or server are needed between ASN and the home CSN. Figure 3.11 shows the roaming AAA framework.

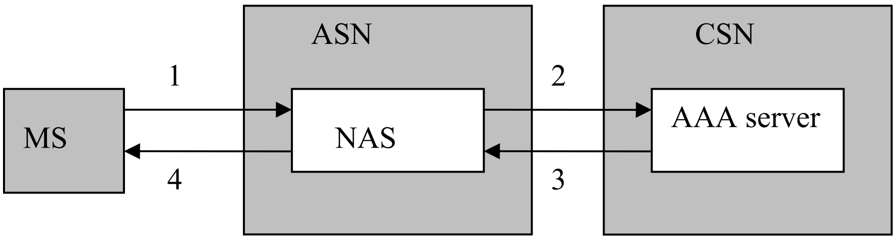


Figure 3.10 Non-roaming AAA Framework

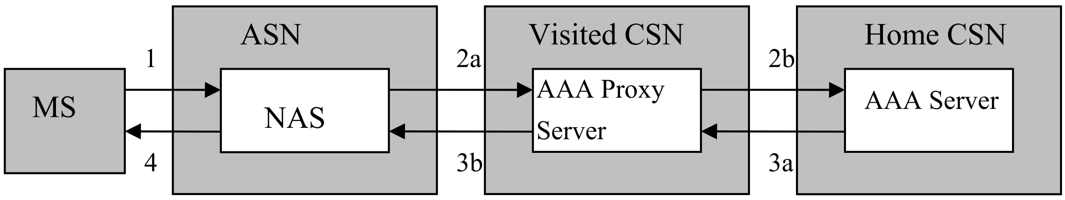


Figure 3.11 Roaming AAA Framework

WiMAX supports device and user authentication using IETF EAP protocol. PKMv2 is the basis of WiMAX security. PKMv2 supports both user and device authentication between MS and home CSN. In the WiMAX network architecture, authentication and authorization are based on EAP. PKMv2 must be used between MS and ASN. EAP message are transferred within ASN. EAP runs over remote access dial-in user service (RADIUS) between AAA server and authenticator in ASN. There are different EAP methods. These methods support different credential types, such as subscriber root key (SUBC), device certificate and device preshared key (Device-PSK).

Figure 3.12 [8] shows the PKMv2 procedures to initial network entry of the MS. There are nine steps.

1. **IEEE802.16e network entry initiation:** Then initiation starts with sending messages between MS and ASN. During the message exchange, the MS and ASN negotiate the PKM version, PKMv2 security capability and

authorization policy and support for device authentication. Finally, the link between BS and MS is established and link activation is sent to authenticator. Then EAP sequence is started.

2. **EAP message exchange:** The authenticator sends an EAP Identity request to supplicant which is MS. Then MS responds with an EAP response message to the authenticator which forwards it to AAA server through RADIUS. After one or more EAP message exchange, the authentication server determines whether the authentication is successful and notifies the MS.

3. **Shared Master Session Key (MSK) and Extended Master Session Key (EMSK) establishment:** MSK and EMSK are established at the MS and the Home AAA Server due to the successful message exchange in step 2. The Home AAA Server transfers the MSK to the authenticator. MSK is used to generate a Pairwise master key (PMK) by MS and authenticator. The MS and Home AAA Server use EMSK to generate mobile keys.

4. **Authentication Key (AK) generation:** AK is generated by MS and the authenticator based on IEEE802.16e specification.

5. **AK transfer:** The AK and its context are delivered to Key Receiver entity by the Key Distributor entity in the authenticator. The Key Receiver caches the messages and generates rest of specified keys.

6. **Security Association transfer:** SA is the set of security information that the BS and one or more of its MS share in order to support secure communications. SA transfer is done by three way handshake procedure. First, the BS sends PKMv2 SA-Tek-Challenge message which is used to identify that an AK will be used for the SA and includes a unique challenge. Second, the MS send response with the PKMv2 SA-TEK-Request message. In the third steps, the BS transmits the PKMv2 SA-TEK-

Response message which contains a list of SA-Descriptors identifying the primary and static SAs.

7. **Traffic Encryption Key (TEK) generation and transfer:** The MS requests two TEKs from the BS for each SA. TEKs are randomly created by the BS encrypted and transferred to the MS.

8. **IEEE802.16e network registration:** After the three-way handshake, the MS exchange message with the BS to perform the network registration. During the message exchange, the MS and ASN negotiate network registration parameters. The completion of registration process triggers service flow and data path establishment process.

9. **Service flow creation:** Service Flow and the corresponding Data Path are started.

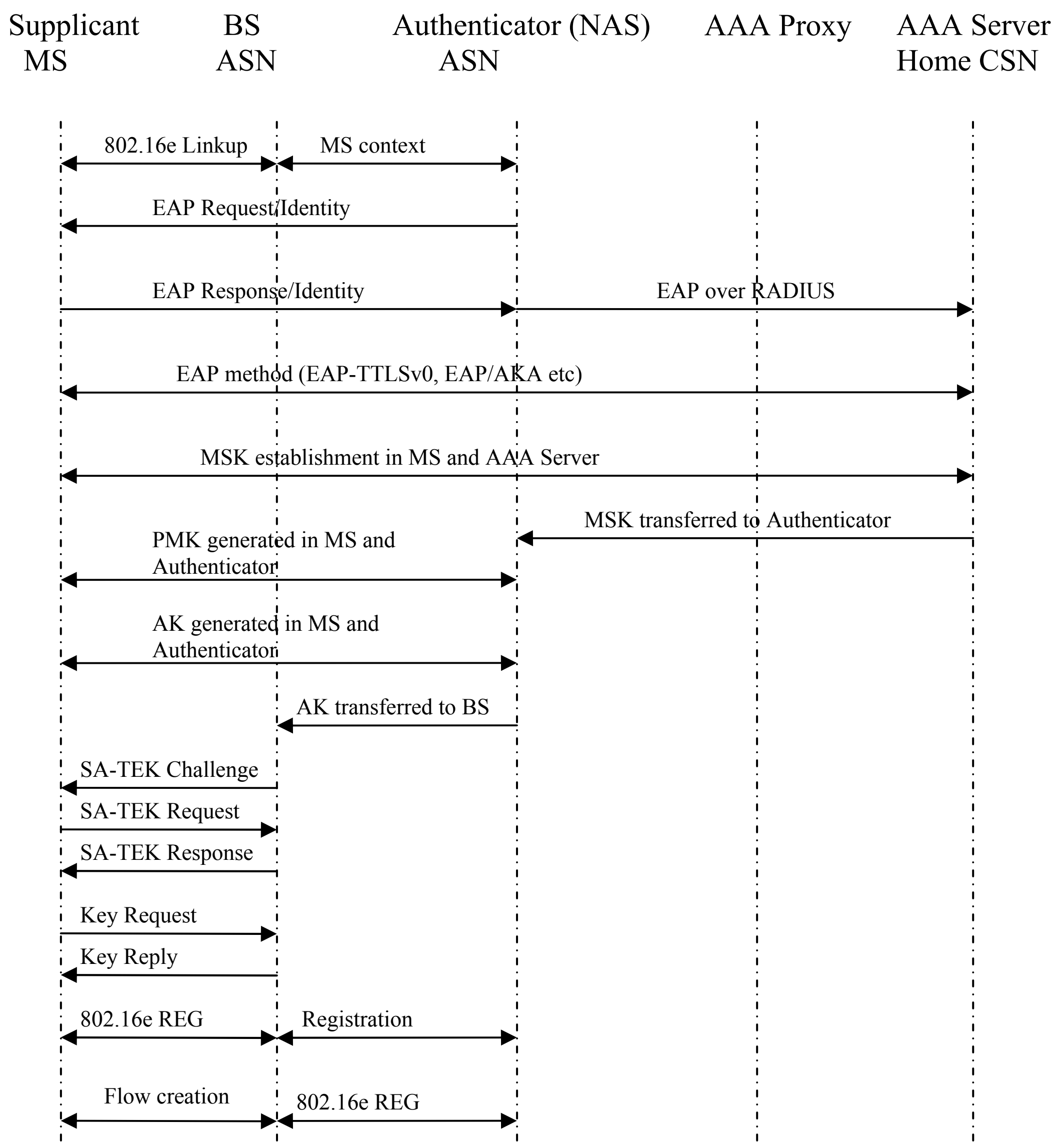


Figure 3.12 PKMv2 procedure

3.4.4 Quality of Service

The QoS architecture framework was developed based on IEEE 802.16e QoS model by NWG. Three procedures are defined as

- Pre-provisioned service flow creation, modification and deletion
- Initial Service Flow creation, modification and deletion
- QoS policy provisioning between AAA and SFA, Service Flow ID management

The WiMAX QoS framework supports both static and dynamic provisioning of service flows. Under the static service model, the subscriber station is not allowed to change the parameters of provisioned service flows or create new service flows dynamically. Under the dynamic service model, MS or BS may create, modify or delete service flows dynamically. In WiMAX Forum Release 1, only static QoS has been covered. But dynamic service QoS may be included in Release 1.5.

The QoS functional model is designed by NWG based on the IEEE 802.16 specification and the Stage 2 architectural reference model. The model is showed in Figure 3.13.

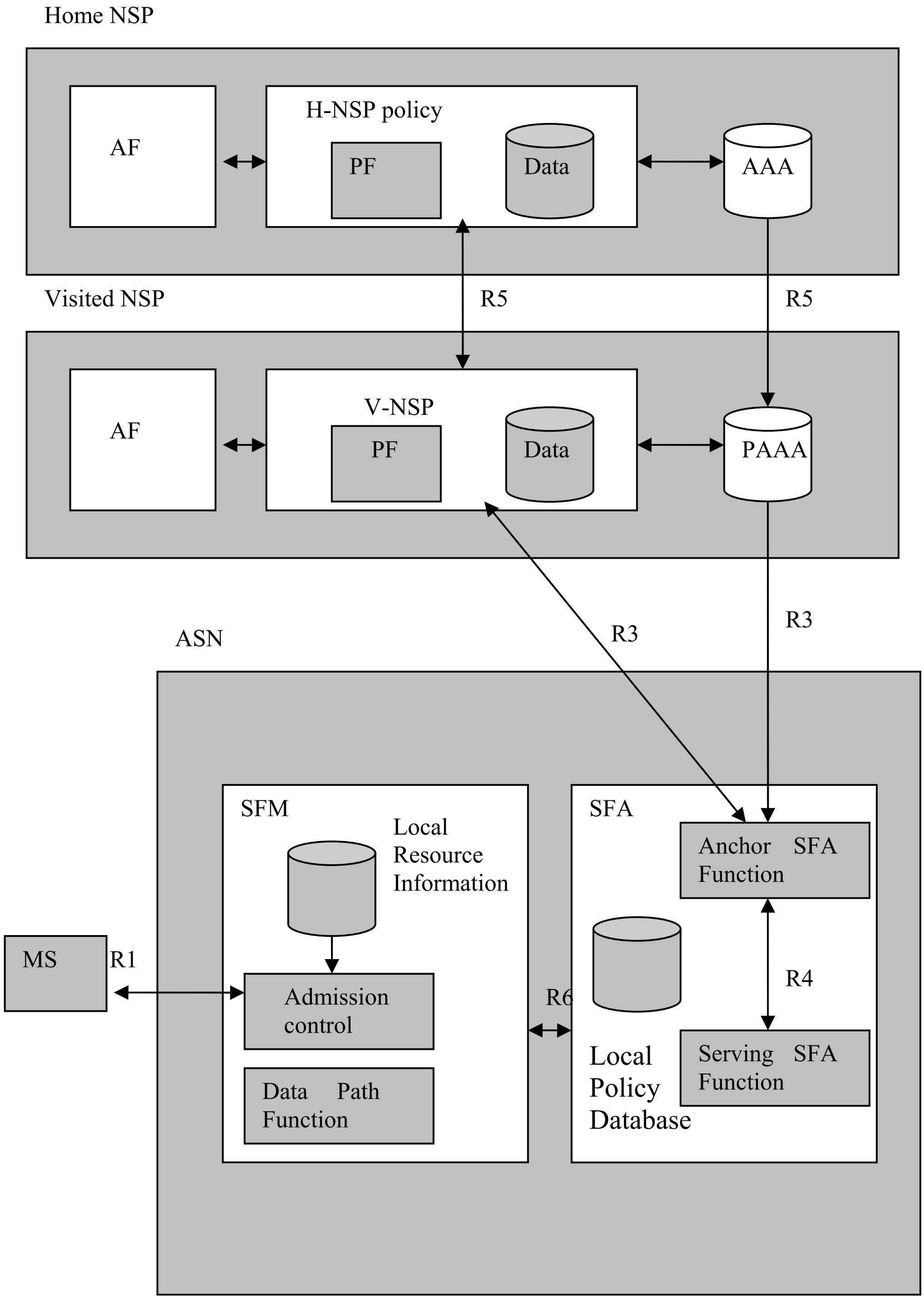


Figure 3.13 QoS functional architecture

The descriptions for the main functional entities are as following:

- **Policy Function (PF):** PF and the database reside in NSP. PF contains information for NSP general policy rules as well as application dependant policy rules. The PF is used to evaluate service requests against these policies. Service request to PF may be from the service flow Authorization (SFA) or from application function (AF).

- **AAA Server:** AAA server contains the user’s QoS profile and associated policy rules. They can be downloaded to the SFA at network entry as part of the authentication and authorization procedure. Then SFA evaluates incoming service requests against the user profile.
- **Service flow management (SFM):** The SFM entity is responsible for creation, admission, activation, modification and deletion or the service flows. An Admission Control (AC) function is included in SFM. AC decides whether a new service flow can be admitted in the network.
- **Service Flow Authorization (SFA):** SFA is located in ASN. When the user QoS profile is downloaded from the AAA into SFA, the SFA evaluates any service request against user QoS profile. Each MS has an anchor SFA. Additionally, one or more SFA entities for the MS to relay QoS related primitives. The relay SFA which communicates with the SFM directly is called serving SFA. If there is no relay, the anchor SFA is also the serving SFA. The anchor SFA and serving SFA perform ASN-level policy enforcement by using a local policy database and an associated local policy function (LPF). The LPF can be used to enforce admission control based on available resources.

3.4.5 Mobility management

The WiMAX network architecture should support mobility requirement. Mobility management is one of the most important issues which should be carefully dealt with when the network architecture is designed. Two types of mobility are supported by the WiMAX network architecture. They are ASN anchored mobility and CSN anchored mobility.

ASN anchored mobility or micro mobility is that the MS moves between Data Path Functions while maintaining the same anchor Foreign Agent at the northbound edge of the ASN network. The ASN anchored mobility management has three functions.

- **Data Path Function (DPF):** DPF is responsible for managing data path setup and the procedures for data packet transmission between functional entities. DPF can be decomposed into 4 parts as Anchor DP function, Serving DP function, Target DP function and Relaying DP function.
- **Handoff Function (HO):** HO is responsible for controlling the overall HO decision operation and performing the signaling procedures related to HO. As the DPF, HO function can also be decomposed into Serving HO function, Relay HO function and Target HO function.
- **Context Function:** This function is responsible for the exchange of state information among the network elements affected by handover. Context Relaying Function is used between the Context Client and Context Server.

The relationship between the functional entities is described in Figure 3.14.

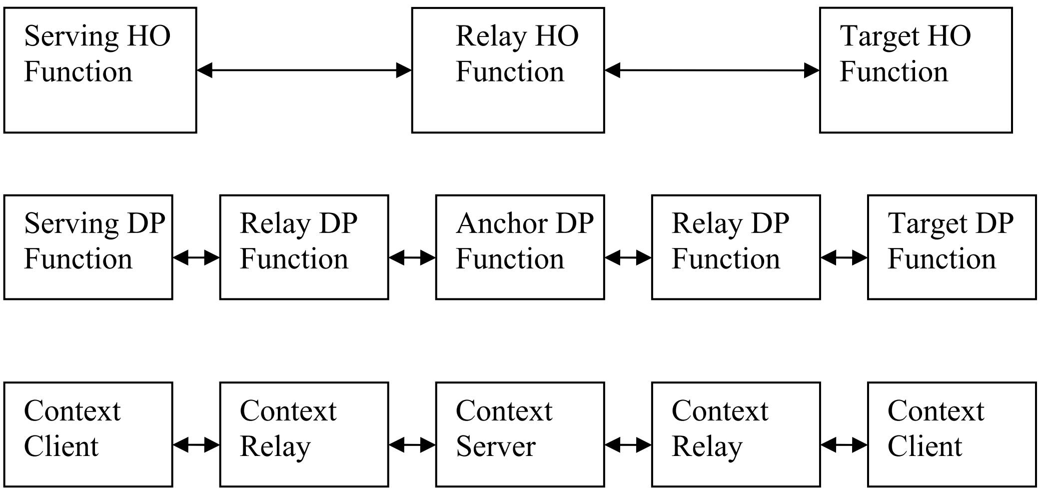


Figure 3.14 ASN anchored mobility management functional entities

CSN anchored mobility can be called as macro mobility. It refers to mobility across different ASNs, especially when FA changes. The new FA and CSN exchange signaling messages to establish data forwarding path. CSN anchored mobility across different IP subsets. Therefore, IP layer mobility management is needed. As discussed in previous section, WiMAX supports IPv4 and IPv6. CSN anchored mobility supports both of them with differences. Two types of Mobile IP (MIP) implementations are defined by WiMAX network for supports CSN anchored mobility. The first one has a MIP client at the MS while the other one has a proxy MIP in the network.

4 WiMAX Deployment

In the chapter 3, we have discussed the PHY layer, MAC layer and Network architecture for WiMAX. To enter the market and provide the services to users, WiMAX should be deployed on the basis of the standards. In this chapter, WiMAX deployment will be discussed. Three sections are included to cover deployment alternatives, available WiMAX product analysis and market status of WiMAX deployment.

4.1 WiMAX deployment analysis

A complete WiMAX end-to-end deployment includes many aspects. However, because the access part of the network contains WiMAX base station equipment, the base station infrastructure and base station backhaul network, it is the dominant factor in the total end-to-end network investment.

4.1.1 Capacity requirement

Before the deployment, it is important to specify the capacity requirement in the deployed area. However, to do this, an investigation for the target city or region should be done. Different cities or regions have their own unique characteristics in different aspects such as area, population density, population growth rate, customer distribution and so on. All of those factors are critical for specifying the requirement. For a big region or metropolitan area, it can be divided into different region types as in Table 4.1.

Table 4.1 Characteristics of Different regions					
	Dense Urban	Urban	Suburban	Rural	Open space
Population	Very large	Large	Moderate	Small	Very few
Height of building	Very high	High	Average	Low	Very low
Density of building	Very high	High	Average	Low	Very low

The coverage requirement should be defined according the standards. The performance under different condition should be described. When doing so, the region characteristics should be taken into consideration. It is necessary to predict the expansion of the region.

Data density defined as Mbps per km^2 can be used to describe capacity requirement. There are different factors which should be taken into account when calculating Data density.

- **Population Density:** This is population density for the whole coverage area.
- **Population Growth rate:** The population growth rate is different from region to region.
- **Addressable Market:** For different services and applications, there are different addressable market groups which are typically categorized by age.
- **Mature Market Penetration:** This varies between different service providers. Even for the same service provider, mature market penetration can be different in different regions. Because the residents in urban or dense urban always have other broadband access alternatives.
- **Mature Customer Mix:** There are different target group defined by the service provider based on the different services or the way they are using

the service. How big portion each type of customer possess affects the capacity requirement.

- **Effect of Mobility and Roaming:** People are moving during the day, especially in the morning when people go to work from home and in the evening when people go back home. This can effect on the data density requirement.
- **Peak Busy Hour (PBH) Activity:** PBH is related to application and customer mix.
- **Desired Performance during PBH:** This is determined by service lever agreement, application, QoS and so on.

With the parameters above, data density can be calculated. Data density requirements for the suburban, rural, and open space areas will be met by simply deploying for ubiquitous coverage, but the dense urban and urban areas will need a deployment plan that adds capacity over time to match the growing customer base and increasing activity levels.

4.1.2 Base Station deployment

Generally, WiMAX base station site can be divided into three major parts. They are site infrastructure, base station equipment and base station backhaul network. The site infrastructure includes site acquisition, antenna towers, backup power units, etc. The operators can either reuse the existing mobile sites or build a Greenfield installation which is more expensive. The base station equipment includes the antenna solutions. Different equipment architecture will be offered by vendors. Operators can select different architecture according the different deployment scenarios. Base station backhaul is the connection to the core network. It could be leased lines or point-to-point wireless link to an aggregation node or fiber node. No matter which approach used, the backhaul capacity must be sized in accordance with the base station capacity.

4.1.2.1 Base Station deployment alternatives

There are many alternatives for base station deployment related to antenna configuration, frequency reuse, frequency band, etc. Each choice made for the deployment can have a significant effect on the performance of the network. It is important to have a clear understanding on the operational tradeoffs for the deployment alternatives.

4.1.2.1.1 Antenna alternatives

Besides conventional multi-antenna solutions Mobile WiMAX supports advanced antenna features, such as Space Time Coding (STC), Spatial Multiplexing (SM) and Adaptive Beamforming. Table 4.2 [14] shows a summary of STC, SM and Adaptive beamforming. Nt and Nr refer to number of transmit antennae and number of receive antennae.

Table 4.2 Advanced antenna options

	Space Time Coding (STC)	Spatial Multiplexing (SM)	Adaptive Beamforming
Downlink	$Nt=2$, $Nr\geq 1$ Matrix A	$Nt=2$, $Nr\geq 2$ Matrix B, Vertical Encoding	$Nt\geq 2$, $Nr\geq 1$
Uplink	n/a	$Nt=1$, $Nr\geq 2$ Two-User Collaborative	$Nt\geq 1$, $Nr\geq 2$

Combining the advanced antenna features, we can provide four alternatives for antenna configuration.

- **SIMO (1x2):** Both the downlink and uplink signal strength are improved compared to SISO because of the effect of multipath. Diversity and maximal ratio combining techniques are used to improve the received signals.
- **MIMO (2x2):** STC and SM can be used to improve the downstream performance. MIMO with STC is known as MIMO Matrix A which sends the same data streams by each transmit antenna to provide space and time

diversity. STC can improve the SNR of the received signal at the mobile station to enhance DL capacity and DL range in a rapid fading multipath environment. MIMO combining with SM called MIMO Matrix B sends a different downlink data streams. Multipath is used to distinguish the different data streams so that DL capacity can be doubled. However, to take the best advantage of both techniques, Adaptive MIMO Switching is used to switch between Matrix A and Matrix B according the channel conditions.

- **Adaptive Beamforming:** Adaptive beamforming can be implemented in three different ways. The first is Switched Beam which provides the ability to switch between several narrow beam antennae or between different beams in an antenna array. The second is Dynamically Phased Array which uses a Direction of Arrival (DoA) algorithm from the user to dynamically direct the beam. Both of these approaches enhance the received signal strength and therefore can provide range and channel capacity improvement but are also subject to angle spread due to scattering and multipath, especially prevalent in urban and many suburban environments [15]. The third approach is known as Adaptive Array or Adaptive Beamforming within which the beamforming parameters are adaptively determined based on both channel and interference condition. This can also enable the array to not only maximize signal strength to the desired user but also provides a mechanism to null out interference [14]. Although high mobility makes it more challenging to get accurate channel estimation due to the rapidly changing channel condition, experimental results have reported an average SIR increase up to 10 dB in an urban mobile environment [16].
- **MIMO with Adaptive Beamforming:** MIMO combining Adaptive Beamforming can be used as another antenna solution. Matrix A with beamforming can increase the channel robustness in a rapid fading

multipath environment and Matrix B with beamforming takes advantage of multiple data streams for added throughput performance.

4.1.2.1.2 Frequency reuse

There are two frequency reuse configurations for a multi-cellular deployment with 3 sector base stations. They are a sector with reuse 1 and with reuse 3. With reuse of 1, the same channel is deployed in each of the three base station sectors. Reuse 1 has the advantage of using the least amount of spectrum. A pseudorandom subcarrier permutation scheme along with channel segmentation is employed to mitigate co-channel interference (CCI) at the sector boundaries and at the cell edge. This causes sacrifices of some downlink channel capacity because some subcarriers will not be fully utilized throughout the entire cell.

Reuse 3 approach assigns a unique channel to each sector. As a result, if we the same channel bandwidth is used, a 3-sector base station deployment needs three times as much spectrum as reuse 1. By using this approach, CCI at the sector boundaries is eliminated and the CCI between neighboring cells is also decreased. Adjacent Channel Interference (ACI) at the sector boundaries is controlled by the orthogonal nature of the subcarriers inherent with OFDMA [14]. The spectral efficiency of each channel is increased while three times of spectrum are used.

However, due to more spectrum are used in Reuse 3, it makes the overall spectral efficiency lower than Reuse 1. Additional spectrum causes the Reuse 3 is more expensive than Reuse 1. Therefore, the frequency reuse model should be chosen according the performance requirement and operator’s financial situation.

4.1.2.1.3 Other deployment factors

Besides the discussed factors also many other deployment aspects should be taken into consideration. Those factors have impacts both on the system performance and deployment cost.

- **Frequency band:** Two frequency bands have been defined by WiMAX Forum. One is from 2300MHz to 2690MHz and the other one is from 3300MHz to 3800MHz. The frequency band impacts some frequency-dependent parameters, such as building/vehicle penetration loss, propagation model, antenna gains, link margins, etc.
- **Channel Bandwidth:** The IEEE 802.16e-2005 supports channel bandwidth from 1.25 to 20MHz. The approved profiles support 5, 7, 8.75 and 10 MHz currently. The wider channel bandwidth has higher capacity and therefore, it will more cost effective to deploy a larger channel bandwidth.
- **UL Link Budget:** In most cases, UL link budget is a factor limiting the range and coverage area of a WiMAX base station. Fortunately, the UL data rate is much lower than DL data rate for most of applications.
- **Duplexing:** There are two types of duplexing as discussed in previous chapters. One is Time Division Duplex (TDD) and another is Frequency Division Duplex (FDD). TDD is the only one currently approved in the WiMAX profile. TDD has many advantages over FDD. An important advantage for TDD is that it assures channel reciprocity between uplink and downlink, which is very important for Adaptive Beamforming. In addition, TDD can adapt to asymmetric traffic condition, which is very important for the throughput of data-centric traffic. Though TDD has many advantages, FDD is expected to be included in future Mobile WiMAX profiles. It can be used in specific market where TDD is not allowed due to local regulatory or where FDD is better fit for the channelization scheme.

4.2 WiMAX product development

The development of WiMAX products has had a significant impact on the WiMAX success. After the IEEE 802.16-2004 was approved in June 2004, Intel began shipping the first WiMAX chipset called Rosedale in September 2004. The first WiMAX Forum-certified product for fixed applications was announced in January 2006. Then the product development direction expands to the mobile WiMAX and admits the main focus. During the last three years, the WiMAX product had a great development time. More and more leading equipment manufacturers and component suppliers have been joining WiMAX group and manufacturing WiMAX product and providing WiMAX network solutions. They aim at different areas in the WiMAX solution, such as chip, antenna, components, backhaul, network planning, software, etc. Table 4.3 shows companies which are categorized by their product type. More information about WiMAX vendors can be found in [17]. Due to the new product development, WiMAX deployment has been accelerated. WiMAX market is forecasted to reach $3.5 billion and account for 4 percent of all broadband usage by 2010 [18].

Table 4.3 Suppliers for WiMAX

Product type	Company name
Antenna	PCTEL Antenna Products, ARC Wireless Solutions, European Antennas, Jaybeam Wireless, Laird Technologies, M2 Antenna Systems, mWare Industries, etc.
Backhaul	Bridgewave Communications, Ceragon Networks, DragonWave, EM Solutions, Harris Stratex Networks, RadWIN, etc.
Component	Anatech Microwave Co, Huber + Suhner, Jauch Quartz America, MECA Electronics, Polyphaser, TDK Corporation, etc.
Equipment	Alvarion Inc, Airspan Networks Inc, Samsung Electronics, Cisco System, Huawei Technologies, Nokia Siemens Networks, Nortel Networks, Motorola Inc, ZTE, etc.
Semi-conductors	Intel Corporation, Fujitsu Microelectronics, Wavesat, Beceem Communications, Comsys Communications, NextWave Wireless Inc, Runcom Technologies, Inc, etc.
Network planning	EDX Wireless LLC, FORSK, Provision Communications, Mentum S.A. , etc.
Software solution	Aptilo Networks, Alianza, Aricent Inc, Bridgewater Systems, Proximetry Inc, etc.
Testing solutions	Agilent Technologies, Anritsu Company, Berkeley Varitronics, Keithley Instruments, Mobile Metrics Inc. Rohde &Schwarz Inc, Wireless Logic Inc, etc.
Billing system	Eyebill Plc, Alepo USA, Aria Systems, IntralSP, etc.

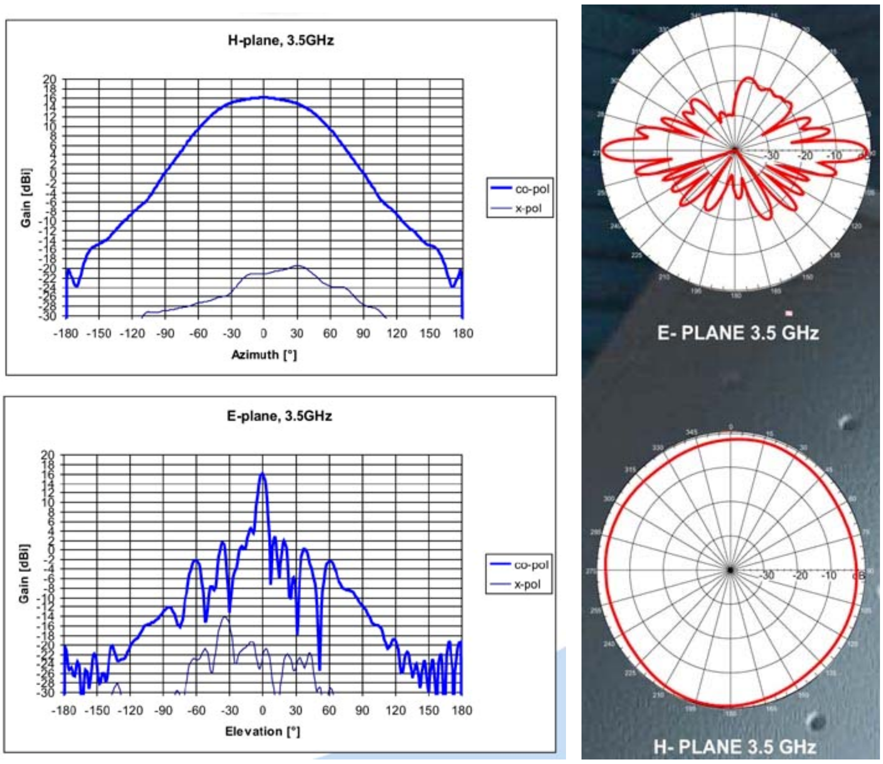
When the main products keep improving their capacity and adding new features, there are also more and more new types of products coming into the WiMAX market. Especially, the appearances of many end user devices help to attract more and more subscribers for WiMAX. The development status for various types WiMAX products are showed as follow.

4.2.1 Chipset

WiMAX chip is the basis of building any CPE. Therefore, it determines the development speed of WiMAX. Intel as a chip producer has been the leader for WiMAX chip design since it delivered the first chipset for fixed WiMAX in 2004. Then the chips have been developed to support both fixed and mobile WiMAX. Intel developed a WiMAX chipset which integrates Intel® WiMAX Connection 2400 Base Chip and Intel® WiMAX Connection 2300R Triple-Band Radio/Intel® WiMAX Connection 2310R Radio System-in-Package. This chipset solution enables WiMAX to be integrated into laptops, Mobile Internet Devices (MIDs), smart phones, cameras, etc. Intel® WiMAX Connection 2250 which provides an integrated System-on-Chip (SoC) enables standalone CPE for high bandwidth usage. Intel® WiMAX/WiFi Link 5350 and Intel® WiMAX/WiFi Link 5150 are wireless network adapters for IEEE 802.16e and 802.11a/b/g/Draft-N1. They operate in the 2.5GHz spectrum for WiMAX and 2.4GHz and 5.0GHz spectra for WiFi. They deliver up to 13Mbps downlink and 3Mbps uplink over WiMAX and up to 450Mbps Tx/Rx over WiFi. They are integrated in Intel® Centrino® 2 processor technology notebooks to provide connectivity to both WiFi and WiMAX.

4.2.2 Antenna

Antenna is the main component for building the WiMAX Smart Antenna System (SAS) which is used in base stations, backhaul connections and CPEs. Its performance has a significant impact on the system capacity and service quality. Based on the radiation pattern, antennae can be classified into two types as Omni-direction antenna, directional antenna. Omni antenna radiates and receives equally in all directions while directional antenna radiates greater power in one or more directions to reduce the interference from the unwanted sources. Sector antenna and flat panel antenna are two types of directional antenna in the market. A radiation pattern comparison for Omni antenna and sector antenna is showed in Figure 4.1 [19].



Sector antenna Omni antenna

Figure 4.1 Radiation pattern comparisons between sector antenna and omni antenna

The key parameters for antenna are frequency range, gain, polarization, azimuth beamwidth and elevation beamwidth. Different antenna suppliers offer a big variety of antenna with different features. The typical frequency ranges are 700MHz, 2300-2700MHz, 3300-3800MHz and 4900-5850MHz. The applied polarization can be vertical, horizontal or dual ±45º. Azimuth beamwidth for sector antennas are typically 45, 60, 90 and 120 degree while it is 360 degree for omni antenna.

Different antenna should be chosen according the requirement. Table 4.4 shows a product range example from Laird Technologies.

Table 4.4 Product range from Laird Technologies

	Product name	Frequency (MHz)	Gain (dBi)	Azimuth Bandwidth(º)	Elevation Bandwidth(º)	polarization
Base station	700MHz Sector antenna	710-790	16	60	14	vertical
	ETSI CS Polarity sector antenna	2300-2700	18(60º), 16(90º)	60 or 90	7	dual
	Standard VPOL sector antenna	2300-2700	20(45º), 17(60º), 17(90º), 16(120º)	45,60, 90,120	8	vertical
	Standard HPOL 5GHz sector antenna	5400-5850	17(90º), 16(120º)	90,120	6	Horizontal
	Wide band VPOL omni antenna	3300-3800	9	360(Horizontal), 8(vertical)		Vertical
	High Gain VPOL omni antenna	5470-5850	12	360(Horizontal), 7(vertical)		Vertical
Backhaul	3.5G Grid Dish antenna	3400-3600	17(1'), 20(2'), 25(3')	15(17dBi), 10(20dBi), 7(25dBi)		Vertical or Horizontal
	3.5 Solid Dish antenna	3300-3600	25(2'), 28(3')	10(25dBi), 8(28dBi)		Vertical or Horizontal
	ETSI TS5 5GHz Wide Band Solid Dish antenna	4940-5850	29(2'), 32(3')	6(29dBi), 4(32dBi)		Vertical or Horizontal or Dual polarity
	5G Hz Wide band Grid Dish antenna	4940-5850	21(1'), 25(2'), 28(3')	10(21dBi), 6(25dBi), 4(28dBi)		Vertical or Horizontal
Client devices	700MHz 6dBi panel antenna	710-750	6	8		Vertical or horizontal
	2.5GHz Wide band Radio Compartment panel	2300-2700	15	30		Vertical or Horizontal
	3.5GHz high gain panel antenna	3400-3600	17	16		Vertical
	5GHz panel antenna	5150-5850	19 or 24	16 (19dBi), 8(24dBi)		Vertical or Horizontal

4.2.3 Base Station and CPE

The WiMAX base station is one of the most critical elements in the WiMAX network solution. There are many different types of base stations available in the market. They are designed for supporting both fixed WiMAX and mobile WiMAX. More and more advanced features improve the capacity and the throughput, such as support of Adaptive Antenna System, multi channel Transmitter/Receiver diversity, support of Space Division Multiple Access, GPS Clock Synchronization, Turbo Coding, etc. Different Base stations are also designed for different Macro cell, Micro cell and Pico cell applications.

On the user's side, many outdoor and indoor CPEs are developed to build the communication with Base station. In addition to performance, convenience, reliability and security are also the key issues which should be taken into consideration when designing CPE. Many of CPEs in the market offer both WiMAX and WiFi. There are dual mode CPEs which support both IEEE802.16-2004 and IEEE802.16e-2005. And more and more Wave 2 CPEs certified by WiMAX Forum are emerging in the market. WiMAX voice CPEs are more required by emerging markets where voice service is the major demand. WiMAX data CPEs have the main market in the developed counties where mobile broadband service is the major demand.

Figure 4.2 and Figure 4.3 show network architectures built by Airspan Networks Inc which produces Base stations and CPE.

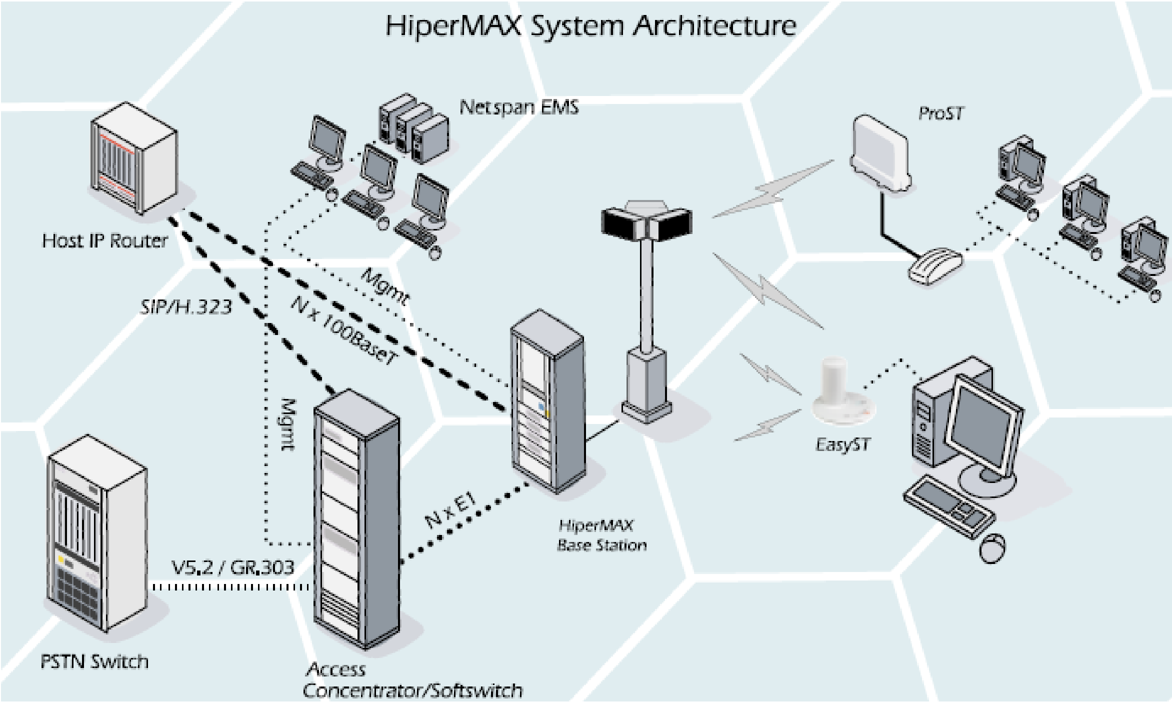


Figure 4.2 Macro cell application architecture

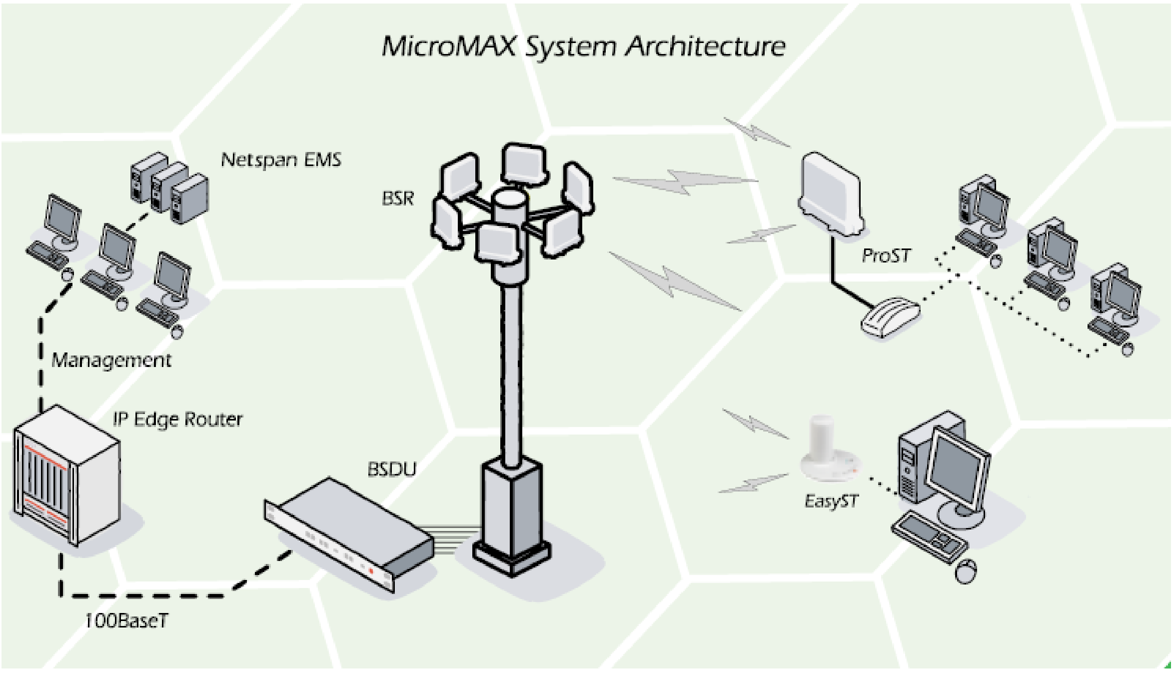


Figure 4.3 Micro cell application architecture

4.3 Market status of WiMAX deployment

Frequency band is a critical element for WiMAX deployments and it is one of the major costs. The uniform allocation of spectrum worldwide can lower the costs for deployment which can accelerate the WiMAX development speed. Yet, the allocation of the spectrum varies from country to country by the government with different spectrum policies. Generally, there are three main frequency bands available for WiMAX in the world, though few countries have all three bands. The most widely allocated band is licensed 3.5GHz band which covers frequencies from 3.3GHz to 3.8GHz. However, United States is not covered by this band. In United States, licensed 2.5GHz band is used. The band is from 2.3GHz to 2.7GHz. This band is also used by other countries, such as South Korea, Australia, Mexico, and Brazil and so on. Another band is License-Exempt 5GHz which is from 5.0GHz to 6.0GHz. Only a minority of countries require a license to use this band for commercial applications and others have requirements referred to as “light licensing” to coordinate use with legacy applications. This band is used in underserved areas with low population such as rural area. Besides, opportunity to use lower frequencies emerges in some countries. Bands lower than 1GHz are generally used for analog TV transition. With the development of the digital TV, television transition is switching from analog to digital broadcasting. In January 2008, 700MHz wireless spectrum was auctioned for commercial usage in the United States. It is believed that this is going to be the trend for the other counties especially for the developed countries. A frequency deployments map in 2008 is showed in Figure 4.4 [20]. Above-mentioned 700MHz band is not showed in the figure.

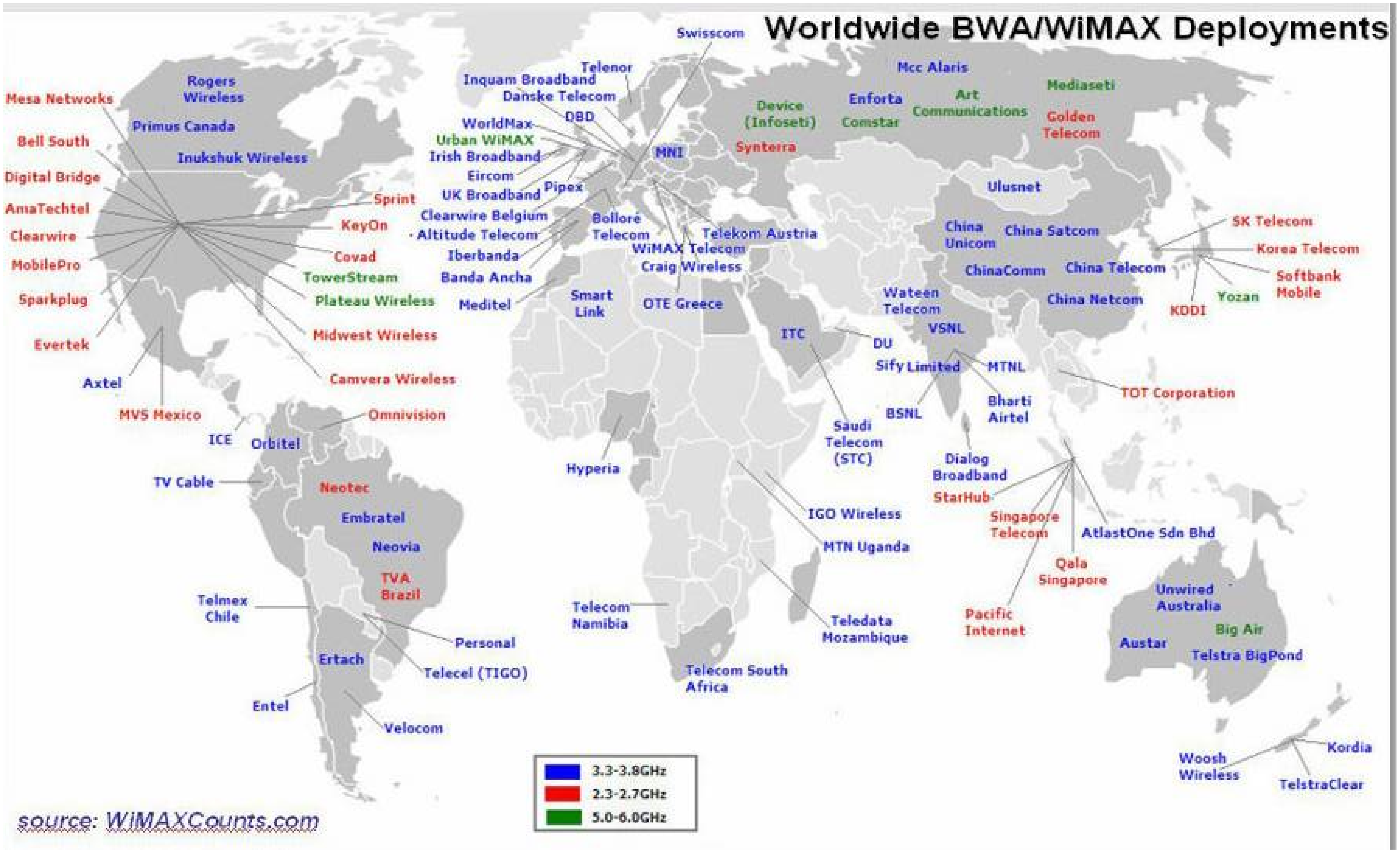


Figure 4.4 Frequency deployment map

With several years' development, WiMAX has been deployed in many countries and regions. Figure 4.5 shows a WiMAX deployment map for the whole world. More detailed information for the deployment map can be found in [21]. The map includes finished deployment, planned deployment and under-going deployment. As the map shows, IEEE802.16d has a wider coverage than IEEE 802.16e. The developed countries have better WiMAX coverage than the developing countries. The already available infrastructure in developed countries makes the development relatively easier and cheaper. However, WiMAX market in developing countries has also been increasing. WiMAX is used to provide the basic voice communication service in developing countries while it focuses on multimedia services in the developed countries. The map does not show any deployment in China but many Chinese telecom carriers have being testing WiMAX during the past two years. WiMAX did not get license for commercial business as 3G technology in the beginning of this year while TD-SCDMA, WCDMA, CDMA2000 did. Yet, China is a big potential market for WiMAX but the WiMAX deployment is still depending on the attitude of Chinese Government towards WiMAX and the market positioning by Chinese telecom carriers.

There has been estimation that WiMAX business will continue growing in the following 3 years. However, it also faces challenges, such as the reducing subscribers due to economy crisis, the development of other 3G technologies and spectrum limitations.

Figure 4.5 WiMAX deployment map

5 WiMAX development trend

WiMAX has been developing relatively fast since IEEE 802.16-2004 was released only 5 years ago. Major operators in many countries have deployed the WiMAX solution. There are hundreds of suppliers for equipment, components and handset who are designing and producing products for WiMAX. The total amount of subscribers has reached 2.68 million in Q3 2008 according the study by Canada-based wireless technologies analyst Maravedis. There are estimations which tell the WiMAX will continue booming for next three to five years. At the same time, there has been a debate on what will be WiMAX's role in the future telecommunication industry. In this chapter, the future development of WiMAX will be discussed.

In spite of the fact that WiMAX had a big growth in 2008, we have already seen the speed slowing down due to the economy crisis. Before looking forward to the future of WiMAX, we will analyze how WiMAX ecosystem is affected by economy crisis during and after the crisis.

5.1 WiMAX development in economy crisis

Like the other industries, telecommunication industry has also been heavily affected by the ongoing economy crisis. As a new technology which just started to grow, WiMAX could be hit even harder. The crisis started as a financial crisis in which banks stop lending money and people stop buying. Thus, many operators can not find the funding to expand their networks and deployment is slowing down in developing countries like India, Russia and Brazil which are potential large markets for WiMAX. In addition, some planned deployment projects have been suspended or canceled. The deployment slow-down leads to reduced requirement for equipments. Especially small suppliers are under big pressure and some of them have to cut expenditure.

Because of the crisis, consumers are spending less. Subscribers for WiMAX services are also declining. Figure 5.1 [22] shows the subscriber analysis result from MIC (market consulting institute). Though number of subscribers has been increasing from 3rd quarter of 2007 to 3rd quarter of 2008, the increase rate started declining in 2008 due to the economic crisis and it is estimated to be worse in 2009 when the economy recession is going deeper. This has a direct impact on the WiMAX handset vendors. The development of new WiMAX handset devices will be delayed and this may pull WiMAX into a dead cycle.

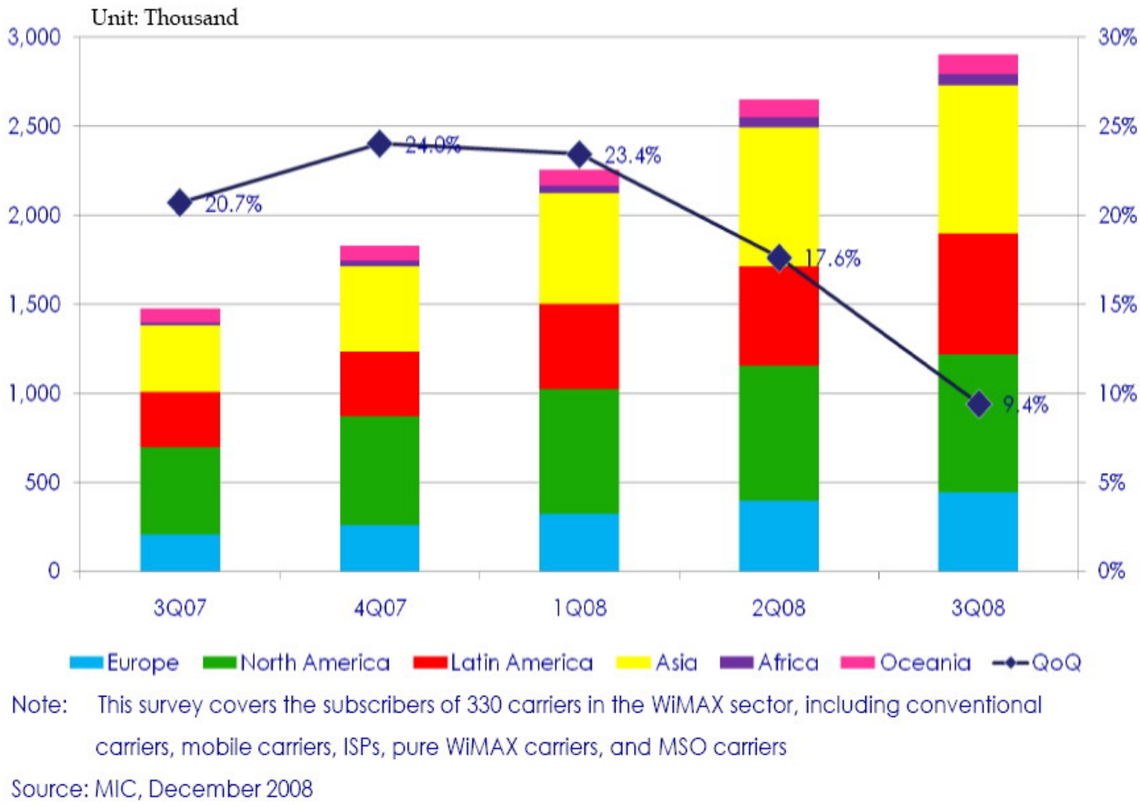


Figure 5.1 Worldwide WiMAX subscribers

Comparing to WiMAX, 3G faces a relatively better situation due to that most of 3G operators have stronger foundation. The harder situation for WiMAX makes many telecom companies reconsider their technology strategy. Some of them have even given up WiMAX and switched to LTE instead. WiMAX has time advantage over LTE but the economic crisis will reduce this advantage. The lasting period of this crisis may potentially determine the market share and future development of WiMAX.

5.2 The future of WiMAX

5.2.1 Development of IEEE 802.16m

We will be out of the economy crisis eventually and it is expected that WiMAX will continue to develop. IEEE 802.16m is under development as the future amendment of IEEE 802.16-2004 and IEEE802.16e-2005 by IEEE 802.16's 802.16 Task Group m (TGm). This standard amends the IEEE 802.16 Wireless MAN-OFDMA specification to provide an advanced air interface for operation in licensed bands [23]. It targets on meeting the IMT Advanced requirements which is seen as a 4G system beyond IMT-2000. The data rates will reach 1Gbps for fixed applications and 100Mbps for mobile applications. IEEE 802.16m will admit the backward compatibility to WiMAX standards.

To get an overview of the IEEE802.16m, the main requirements are listed as followings. However the system requirement document has not been through the evaluation by ITU and there might be some changes in the future. More detailed information can be found in [23].

General requirements

- **Legacy:** IEEE 802.16m shall provide the support and interoperability for the legacy Wireless MAN-OFDMA equipment, including MSs and BSs and it shall have the ability to disable legacy support.
- **Complexity:** IEEE 802.16m shall minimize complexity of the architecture and protocols and enable interoperability of access networks.
- **Services:** IEEE 802.16m shall support legacy services and be more flexible to support services for next generation mobile networks. IMT-Advanced

QoS requirements should be supported including end-to-end latency, throughput and error performance.

- **Operating frequencies**: IEEE802.16m should operate in lower than 6GHz frequencies and be deployable in licensed spectrum allocated to the mobile and fixed broadband services. It shall be able to operate in IMT-Advanced identified frequencies.
- **Operating bandwidths:** IEEE802.16m shall support scalable bandwidths from 5 to 40MHz which could be supported by single or multiple carriers.
- **Duplex schemes:** Both TDD and FDD are supported by IEEE 802.16m. Full duplex and half duplex MS operation are supported in FDD mode.
- **Advanced antenna techniques:** For the BS, IEEE 802.16m shall support a minimum of two transmit and two receive antennas. For the MS, it shall support a minimum of one transmit and two received antennas.
- **Government mandates and public safety:** IEEE 802.16m shall support public safety first responders, military and emergency services.

Functional requirements

- **Peak spectral efficiency:** IEEE802.16m shall support 8bps/Hz for baseline downlink and 2.8bps/Hz for baseline uplink, and 15bps/Hz for targeted downlink and 6.75bps/Hz for targeted uplink**.**
- **Latency:** Latency should be reduced as compared to the Wireless MAN-OFDMA Reference System for all aspects.
- **QoS:** IEEE 802.16m supports all QoS classes which enable new applications. And it should provide support for preserving QoS during handover with other Radio Access Technology (RATs).
- **Radio resource management:** Measurement/reporting, interference management are used to utilize the radio resource management.

- **Security:** IEEE 802.16m should provide security functions to achieve integrity protection, user traffic and user data protection and secure access.
- **Handover:** IEEE802.16m shall provide handover within and between all cell types in the system. And it should support handover with other RATs.
- **Enhanced multicast broadcast service:** IEEE 802.16m shall support enhanced multicast service and switching between broadcast and unicast services.
- **Location based services:** IEEE 802.16m shall support location based services.
- **Reduction of user overhead and system overhead:** Compared to the Wireless MAN-OFDMA Reference System, IEEE 802.16m improve the reduction of user overhead and system overhead.
- **Power saving:** IEEE 802.16m should provide enhanced power saving functionality.
- **Multi-RAT operation:** IEEE 802.16m shall support efficient handover to other radio access technologies, such as IEEE 802.11, 3GPP GSM, and UTRA CDMA2000.

According the time table [24] from TGm, the System Requirement Document (SRD), Evaluation Methodology Document (EMD) [25] and System Description Document (SDD) [26] will be ready during the first half year 2009. And the IMT Advanced Proposal will be ready for evaluation by ITU-R by September. Then the proposal will be refined according to the feedback from the evaluation result. The letter ballot and sponsor ballot for the 802.16m Amendment will be done by May 2010. The radio interface Recommendation developed by ITU-R will be ready in fourth quarter 2010.

5.2.2 Competition between LTE and WiMAX

Fourth Generation (4G) technology includes Long Term Evolution (LTE), Ultra Mobile Broadband (UMB) and WiMAX. LTE is upgrade on Universal Mobile Telecommunications System (UMTS) provided by 3rd Generation Partnership Project (3GPP). LTE is seen as a response to the WiMAX technology by the mobile cellular carriers. UMB is an improved technology based on CDMA2000 by 3GPP2. However, Qualcomm which is UMB’s lead sponsor, announced it switch its interest to LTE. Most CDMA carriers in USA, Canada, China and Japan have announced plans to adopt either WiMAX or LTE as 4G technology. Therefore, the competition will be between LTE and WiMAX as 4G technology takes place and there has been a debate on which one of them will be the future 4G.

Both LTE and IEEE 802.16m aim at meeting the IMT Advanced requirements which is to achieve 100Mbps for mobile application and 1Gbps for fixed-nomadic application. Table 5.1 shows the comparison between WiMAX and LTE. Both of them are based on SOFDMA and MIMO technology. These two standards are still under development by IEEE and 3GPP. From the technical point of view, there will not be much difference between two technologies.

Table 5.1 Comparison between WiMAX and LTE

	WiMAX 802.16e	IEEE 802.16m	LTE
Network equipment available	2007	2010	2009
Handset available	2008	2011	2010
Organization	IEEE & WiMAX Forum	IEEE & WiMAX Forum	3GPP
Radio technology	SOFDMA	SOFDMA	SOFDMA
Antenna technology	MIMO & AAS	MIMO & AAS	MIMO & AAS
Duplexing	TDD	TDD & FDD	FDD
Frequency bands	2300, 2500, 3500, 5000	Under 6GHz	700, 850, 900, 1800, 1900, 2100, 2500 MHz
Channel bands	1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz	5-40MHz	1.4MHz, 1.6MHz, 3.5MHz, 10MHz, 15MHz, 20MHz
User plane latency	< 20	<5	<5
Control plane latency	< 100	< 100	<100

WiMAX have being deployed at least 2 years ahead LTE. The whole ecosystem for WiMAX has been built in this 2 years and the deployment has been done in many major markets in the world. However, unlike WiMAX, which requires to build a new network, LTE only needs to make upgrade for the existing UMTS infrastructure which is already used by over 80 percent of mobile subscribers globally. This is one of the reasons that many carriers intend to support LTE. Compared to LTE, WiMAX faces the lack of high quality spectrum. In most countries in the world, the available spectrum for WiMAX is still limited to 3.5GHz or 5GHz. The higher frequency spectrum makes WiMAX need more base stations to cover the same area than LTE.

However, which one will win the competition is hard to forecast. Both of them have their own advantages. There are more and more people who believe WiMAX and LTE will coexist as a supplement to each other for long time. Chip manufactures are already looking into the possibility to build a dual-mode chip solution for both technologies. I expect the WiMAX will still keep its two-year-ahead advantage for two or three years and the number of subscribers will keep growing. Then the mobile operators will start to deploy LTE. LTE has the advantage in available infrastructure and experience from 3G. It will take relative short time to catch up. However, how fast both technologies will develop depends on the developing speed of telecommunication industry.

6 Summary

As a broadband wireless solution for Wireless Metropolitan Area Network (WMAN), WiMAX is a good supplement for the existing technology such as Wi-Fi and 3G. The increasing expectations from the subscribers create the big market for WiMAX. The advantages of WiMAX make it be one of the most competitive solutions which can meet the subscribers' demand. Especially, in the underserved regions where no infrastructure is available, WiMAX is a cheaper and faster solution to provide the basic voice service. In developed regions, WiMAX focuses on providing the high rate multimedia services.

From a standard to commercial deployment in the market, WiMAX has been successful so far. The ecosystem of WiMAX has been built during last four years. Different types of WiMAX products have been developed and are available in the markets, including chipset, base station, CPE and end user handset. In 2007 and 2008, the number of subscribers for WiMAX has been increasing fast. More and more operators and equipment manufacturers are entering the WiMAX business. However, WiMAX development and deployment have been affected by the economic crisis. This has happened at the time when the deployment of WiMAX just starts to expand in the world. The influence for WiMAX is more serious than the other 3G competitors due to its immaturity in the market. However, the crisis will not fully destroy the WiMAX business. WiMAX is expected to continue growing after the crisis.

IEEE 802.16m is under development as the future of WiMAX. This makes WiMAX more competitive in the future. However, as a response to IEEE 802.16m, 3GPP is also developing LTE as a 4G solution based the existing 3G network. Both technologies plan to meet the IMT Advanced requirements. There is no big difference between WiMAX and LTE from technology perspective. However, each of them has their own advantages over the other one. It is expected that both technologies will coexist as supplement for each other in long term.

References

[1] ITU. Telecommunications indicators update—2004. www.itu.int/ITU-D/ict/statistics/.

[2] Jeffrey G.Andrews, Arunabha Ghosh, Rias Muhamed. Fundamentals of WiMAX: Understanding Broadband Wireless Networking. Prentice Hall, page35-38, page 54, page285-287, 2007.

[3] WiMAX Forum website, "WiMAX Forum® WiMAX™ Technology Forecast (2007-2012)" page3, 2008

[4] WiMAX Forum, "Mobile WiMAX-Part II: A Comparative Analysis" page 26-27, 2006.

[5] Juha Korhonen, WiMAX versus 3G threat or opportunity, IEE Communication Engineer, 2006.

[6] WiMAX Forum website, "WiMAX Forum™ Mobile System Profile 4 Release 1.0 Approved Specification 5 (Revision 1.4.0: 2007-05-02)"

[7] WiMAX Forum, "Mobile WiMAX-Part I: A Technical Overview and Performance Evaluation", page 20, page 23, 2006.

[8] WiMAX Forum website, "WiMAX Forum® Network Architecture-Stage 2: Architecture Tenets, Reference Model and Reference Points (Release 1.0 Version 4)" Part 0, Part1, Part2, Part 3, February 03, 2009.

[9] WiMAX Forum website, "Recommendation and Requirements for Networks based on WiMAX Forum Certified™ Products-Release 1.5" 7/17/2008

[10] WiMAX Forum website, "WiMAX Forum® Network Architecture-Stage 3: Detailed Protocols and Procedures (Release 1.0 Version 4)"February 03, 2009.

[11] IEEE 802.16-2005 and IEEE 802.16-2004/Cor 1-2005, Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems, February 2006

[12] RFC2132 – DHCP Options and BOOTP Vendor Extensions, S. Alexander and R. Droms, March 1997,Standards track

[13] RFC2904 – AAA Authorization Framework, J. Vollbrecht, et al., August 2000, Informational

[14] WiMAX Forum website, "A Comparative Analysis of Mobile WiMAX^{TM} Deployment Alternatives in the Access Network" page 17, May, 2007.

[15] Wen Tong, "MIMO Will Power WiMAX and Beyond", Presentation at Global WiMAX Summit in China, Oct. 2006.

[16] P.H. Lehne, O. Rostbakken, and M. Petersen, "Estimating Smart Antenna Performance from Directional Radio Channel Measurements", Proceedings 50th IEEE Vehicle Tech. Conf., page 57-61, Sept 1999.

[17] WiMAX.com website, "Buyer's guide to WiMAX" October 1, 2008

[18] G.Subrahmanya V.Radha Krishna Rao, G.Radhamani. WiMAX-A Wireless Technology Revolution. Auerbach Publications, page 117, 2008

[19] http://www.lairdtech.com/

[20] WiMAX Forum website, "Frequency Deployments Map", maravedis Inc, May 2008.

[21] http://www.wimaxmaps.org/

[22] http://mic.iii.org.tw/english "The worldwide WiMAX subscriber base 3Q2007-3Q 2008" December 2008

[23] http://wirelessman.org/tgm/ "IEEE 802.16m System Requirements Document (SRD)" January 1st 2009

[24] http://wirelessman.org/tgm/ "IEEE 802.16m Work Plan" March 12th 2009

[25] http://wirelessman.org/tgm/ "IEEE 802.16m Evaluation Methodology Document (EMD)" January 15th 2009

[26] http://wirelessman.org/tgm/ "IEEE 802.16m System Description Document (SDD)" April 4th 2009